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AN ASSESSMENT OF NOGAPS PERFORMANCE IN POLAR FORECASTING FROM SHEBA DATA

by

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September 2004

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AN ASSESSMENT OF NOGAPS PERFORMANCE IN POLAR FORECASTING FROM SHEBA DATA

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This study evaluates the latest Navy Operational Global Atmospheric Prediction System (NOGAPS) version 4.0 with a comparison to data collected during the Surface Heat Budget of the Arctic (SHEBA) project from October 1997 to October 1998. In particular, three periods from this year long study were the focus and included, a winter, spring, and summer case. For each of these cases the first 24-hour period of the forecasts were analyzed for any bias and root mean square difference from the SHEBA data. NOGAPS had no significant biases in pressure and wind speed. During the winter case, the NOPGAPS surface temperature remained near –28 C while observed temperature varied in response to cloud cover changes and was lower by 5.3 C on the average. During the spring the NOGAPS temperatures had a steady increase from –11 C until reaching the melt season temperature of 0 C 11 days earlier than observed. As a result of too warm a surface and less downwelling longwave radiation, the net longwave flux cooling was greater than observed, by an average of -12.4 Wm^{-2}. The NOGAPS net shortwave radiation was greater than observed by an average of 62 Wm^{-2} for spring and 22.6 Wm^{-2} for summer.

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I. INTRODUCTION

A. NAVY RELEVANCE

The Arctic is an important region for operational numerical weather prediction (NWP) due to its large source of cold air, and the effects it has on mid-latitude winter weather.

Navy Operational Global Atmospheric Prediction System (NOGAPS) is the supporting high resolution global model for all naval operations. It is used by other Navy models as their source for initialization parameters and boundary conditions.

The teleconnections between the severity of mid-latitude weather systems and the intensity of Arctic cold air masses is a key factor in the reasoning behind looking into the way models forecast Arctic weather. If NOGAPS is able to increase the accuracy of its forecasts in the Arctic, a subsequent increase in accuracy for the mid-latitudes is equally likely. This has obvious benefits to the entire Navy community.

Long term forecasts of ice extent would be another issue that can have significant benefits to the Navy. If the Navy could know with a particular level of confidence that there would be a decrease in the amount of ice, they could take advantage of a quick route for ships to reach from one ocean to another. In addition, it would also benefit them to know when other nations could be able to transit these routes.

Considering the implications of polar ice caps getting smaller with every subsequent year, there is likely to be an increased interest in the possibility more traffic will be using the newly opened routes. There are significant advantages for countries to use the Arctic as a route for transport, previously only used by submarine forces. This is a particularly important issue since if more vessels (including submarines) are using these opened passages, more anti-submarine warfare will be required by surface ships.

The previous items are fairly lofty in their possibility of impacting the Navy's way of thinking towards the Arctic. Currently the Arctic is not of great importance to the Navy, but this should not relegate Arctic research to the obsolete pile. There are real world concerns that directly feed from Arctic weather that are of great importance to the

Navy today. As the ice caps begin to thin and recede there is a decrease in the thermal gradient between the mid-latitudes and the poles. This is being accelerated as the caps get smaller since the decrease in albedo will create more heat absorption and subsequently more melting. The impact to the mid latitude weather will likely result in increased storm activity in the mid latitudes as the atmosphere attempts to regain an equilibrium state (Randall et al., 1998). An increase in storm activity will be a major issue with all Navy sea going commands. As storms increase in number and severity there will likely be more need for optimum ship routing for ships at sea, and more ships having to get underway due to approaching storms. These are big budget issues, and if improvements in the model could better forecast the Arctic conditions causing these issues, the Navy is likely to save significant amounts in the yearly budget due to damage and false alarms.

B. BACKGROUND

In recent years there has been a significant focus on Arctic weather and its potential indicator of global climate changes. Much interest has been devoted to the different feedback loops and whether these can be appropriately modeled in an effort to show global scale change in the weather.

Over the last half of the 20th Century several scientific field programs have occurred in the Arctic regions. This exploration has been difficult due to the extreme conditions faced by not only man but by the machines left to take data. In addition, the ice is an ever-changing entity that is driven by the winds and sea. It makes traveling to data collection sites a costly endeavor.

This sets the Arctic apart from much of the rest of the world where humans are capable of maintaining an existence and collecting data with a certain level of ease. This is most apparent when NWP Systems are used in predicting future weather events. There are numerous models around the world with various levels of resolution in both the horizontal and vertical coordinates. Data plays a key role in the ability of a model to appropriately spin up. Without an adequate source of data for the Arctic regions, there are significant differences between a model and actual events taking place. Given the

same level of data, many of the different NWPs will produce drastically different results. This illustrates the lack of a thorough knowledge of the physics acting on the region (Randall et al., 1998).

As the world continues to become more concerned over the effects of global warming, and the number of serious weather related events (such as extratropical cyclone activity in the Pacific north of 60^{o} N) are on the rise, many scientists are focusing on the role the Arctic is playing in these changes. Even though scientists are aware that the Arctic is influencing these changes, it is not clear as to how these changes are all linked together due to the complexity of the system (Randall et al., 1998).

For the Arctic a key aspect in the energy budget is ice cover. Ice cover size, extent, age, thickness, and albedo play into this complex cycle of energy transfer (Curry et al., 1996). Other factors such as CO_2 induced warming, solar radiation, and thermal coupling of open-ocean to atmosphere add another component to the ever complex system. There are several factors that affect the way in which the Arctic warming takes place. These are the different feedback loops important in the budgeting of Arctic energy (Tao et al., 1996). In this particular study the most important of these feedback loops is the temperature-ice-albedo loop.

A key component of the temperature-ice-albedo loop is cloud layers. Dependent upon many factors, if a model handles cloud formations well, it is likely the temperature-ice-albedo feedback loop will also do well. Each of the Arctic seasons has a different set of parameters that are needed for cloud formation (Curry et al., 1996). The seasonal changes in cloud layer types means that any model that attempts to predict Arctic weather must be able to handle cloud changes reasonably well.

C. THESIS FOCUS

The focus of this thesis is to evaluate the performance of the latest version of the NOGAPS model. Model predictions are compared with data collected during the Surface Heat Budget of the Arctic (SHEBA) project with model predictions. Using the two sets of data, statistical methods are used for the short-term forecasts (between 0 and 24 hours) to identify any physics issues that are causing model biases. The main reason for studying short-term forecasts vice long-term forecasts is to simplify the number of error

sources. By looking at the short-term forecasts the effects from the accumulation of model forecast errors is minimized.

SHEBA took place from October 1997 to the following October in 1998 in the Beaufort and Chukchi Seas (Figure 1). This study focuses on three periods during the year when model predictions were performed (Figure 2).

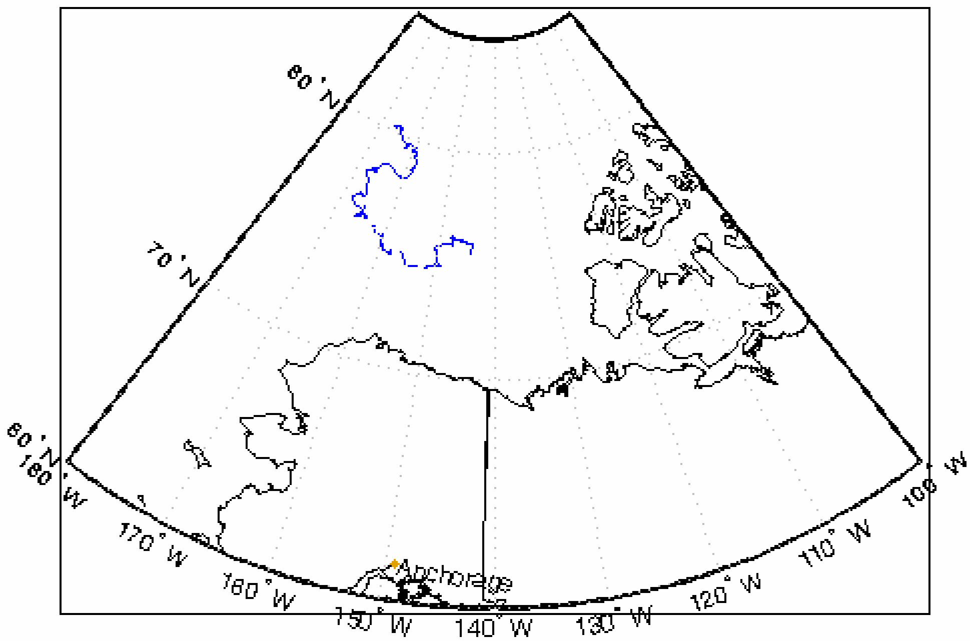

Figure 1. Complete track for SHEBA experiment (blue). Gaps are areas where meteorological surface data were unavailable.

The three time periods cover the following dates. For the winter period, in green on Figure 2, the data covers the period 20 December 1997 to 22 January 1998. The spring period, in red, covers the period 09 May 1998 to 08 June 1998. Summer, the blue track, covers 22 July 1998 to 22 August 1998.

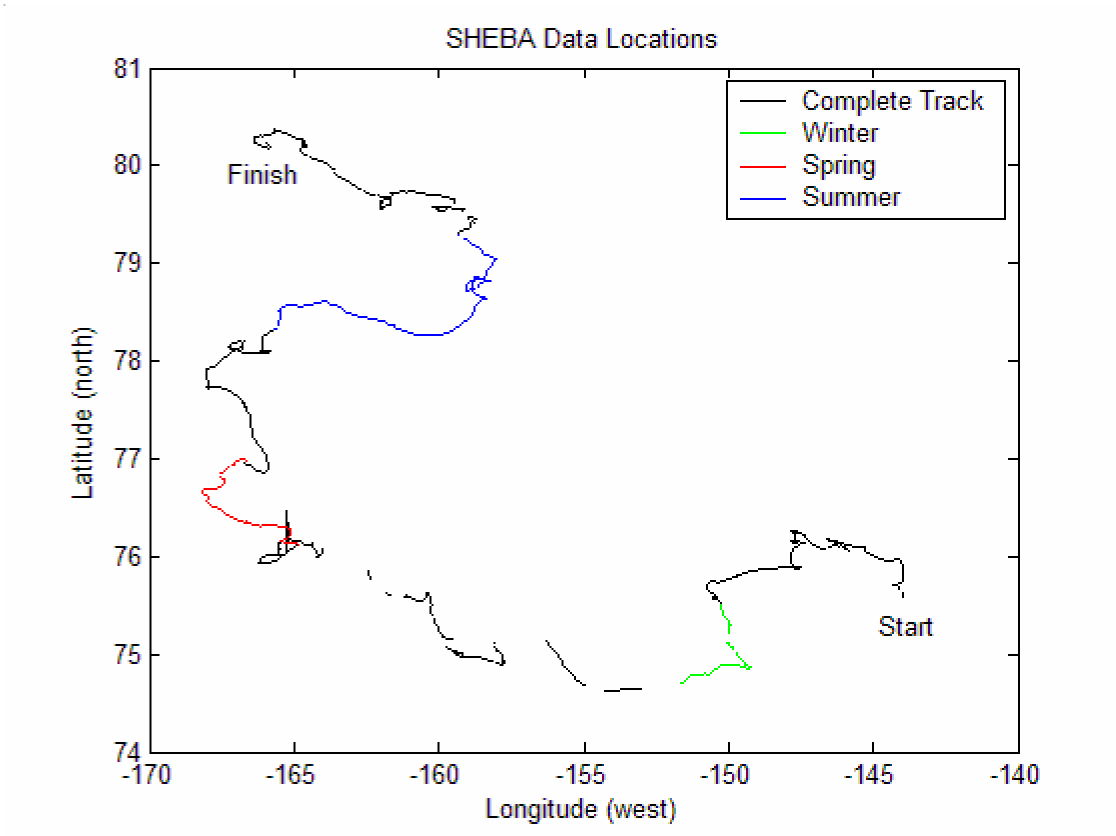

Figure 2. Close up of the SHEBA track, and the locations for the three different time periods compared during this study.

D. NUMERICAL WEATHER PREDICTION SYSTEMS

NOGAPS is a spectral NWP System in the horizontal, with vertical finite differencing sigma coordinates. There are several advantages to the use of a spectral model over other types (such as horizontal finite differencing). One of the largest advantages for using NOGAPS in the Arctic is that there is not a singularity issue near the poles. NOGAPS uses spherical coordinates which eliminates the issue of singularities at the poles. Many models using a finite differencing method use polar coordinates as grid points. For the tropics and mid-latitude regions this is an effective method, but at the poles these grid points continue to come closer together. This requires a very small time step in order to maintain computational stability. It also leads to excessive resolution near the poles, increasing the processing time required. To deal with these particular problems, these models must take special actions to minimize these

effects. One method is through the use of a polar filter which feeds into the main model, but this method has its own concerns and is not an ideal solution to the singularity at the poles issue (Randall et al., 1998).

One problem facing a spectral model is the way in which it interprets the terrain heights used by the model. Due to issues within the model there is a tendency of the model to have negative terrain heights that require corrections to produce a meaningful solution near these areas (Hogan and Rosmond, 1991).

There are also significant differences between different seasons. The Arctic has four seasons that are on similar time scales to the North American seasons. The major difference is that they deal only with whether ice is building, retreating, or remaining constant. In the winter season there is perpetual darkness due to the sun being below the horizon. The snow and ice surface is dry and forms a well-insulated cover over the liquid ocean. Heat fluxes from leads and polynas (ice openings) can be very large. During the spring the sun has made its way partially into the sky. The ice extent and thickness reach maximum values. The snow and ice surface remains dry and the surface and near-surface temperatures have distinct diurnal trends (except near the pole). During the summer, the ice surface melts and is usually wet and at a temperature close to freezing all the time. Ice extent and thickness decrease. In the fall season the ice extent begins to increase again as the sun retreats below the horizon.

During the spring season many NWP models tend to have a significant positive temperature bias of the mean surface temperature (Randall et al., 1998). One of the key factors in determining the surface temperature is the presence of clouds. The average cloud fraction for different NWP ranges from 0.3 to 0.9 (Chen et al. 1995) for spring.

There are other concerns for NWP models in the way they parameterize quantities such as sea ice, clouds, and energy fluxes. Due to the complex nature of these individual elements and their subsequent feedback loops, it is difficult to correctly parameterize an individual item without creating errors in the other remaining properties. (Randall et al., 1998)

Solar radiation tends to be a problem for NWP due to the large zenith angles. The large angle creates issues of how the atmosphere handles the solar flux, and where the interaction is taking place when the sun is visible. Due in part to the lack of the solar energy, the longwave radiation becomes a major factor in the surface energy balance. The winter atmosphere is extremely dry, allowing more longwave radiation from the surface to radiate into space. This allows significant cooling to take place in the near surface atmosphere and the surface itself. As the surface temperature decreases, the primary wavelength for energy transmission from the surface shifts to longer wavelengths, by Planck's function. With the Arctic being the extreme in cold temperatures on Earth, any NWP attempting to model the Arctic must be able to account for this shift in emitting range to properly model the energy transport (Randall et al., 1998).

Another major difference between NWP models is their ability to properly handle the Arctic boundary layer. During the winter this boundary layer is extremely stable. This extreme stability strongly decouples the upper atmosphere from the surface (Curry et al., 1996). Much of the latent and sensible heat fluxes in a region are due to exchanges between the surface atmosphere and open water (leads and polynas). These exchanges can lead to formation of extensive low level cloud cover. There are concerns whether, with the current levels of vertical resolution, that the NWP can accurately represent these features. They are predominantly set up to deal with conditions that are less than stable near the surface (Randall et al., 1998).

As mentioned in the previous section, the focus of this report is to look at the latest version of NOGAPS with its increased horizontal and vertical resolution. The increase in vertical levels is directly focused on the problem associated with being able to model the boundary layer near the surface. This is beneficial to this study, even though only the surface data will be analyzed. It is assumed that if there is better vertical resolution there will be direct impacts to the surface layer and improved quality of forecasts of surface parameters.

Cloud parameterization plays a key role in all of the previous issues. The effects that clouds have on the Arctic weather are far reaching. They impact energy balance,

moisture transport, and albedo issues that play into the complex interactions that create and change the Arctic weather. It is the extent of condensed water in the vertical and horizontal, size, shape, and the phase of the particles that define the Arctic cloud structure. Clouds have a large influence the Arctic energy balance. As mentioned earlier due to their inability to properly parameterize clouds, most NWP have significant biases associated with them (Curry et al., 1996).

Sea ice is not generally a forecasted quantity in NWPs. This has inherent errors associated with the Arctic heat budget. In general sea ice extent has been a specified constant throughout the forecast cycle. The value of the sea ice extent has been calculated from observations and satellite measurements and used until the next observation (which could be as long as a few weeks separation). There are improvements being made currently in the treatment of sea ice in NWP. Understanding the mechanical properties of sea ice is crucial to proper modeling and feedback representation. Ice mechanics affects climate modeling in two ways. The first is the advection of ice out of the Arctic into surrounding oceans, which is a source of freshwater to the ocean circulation system. Second, the thickness of sea ice is directly connected to the transport and deformation of the sea ice. Ice movement also results in the creation and destruction of leads (Randall et al., 1998).

To overcome the lack of data, satellite and remote observation stations have been used to gain crucial real-world data needed to initialize the model in the Arctic region. One of the challenges with data collection is that the Arctic has the greatest level of extremes on the Earth. Two such extremes are the cold temperatures and the low amounts of solar heating. For in-situ measurements these extremes test the level of performance for the equipment making the measurements. Satellites have their own challenges with the small differences in temperature, any equipment noise limits the accuracy of the data collected (Curry et al., 1996).

The above generalities are what the NWP community is facing with accurate Arctic modeling. This study focuses on one particular prediction system, NOGAPS.

1. NOGAPS

NOGAPS is operated jointly by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) and the Naval Research Laboratory (NRL). For the purpose of this study the output forecasts consisted of an analysis through the 24-hour forecast.

The resolution of NOGAPS has been increased many times. The current version of NOGAPS runs on T239 spectral waves of horizontal resolution. This equates to approximately 0.5^{o} resolution. This was a recent increase from T159, a 0.75^{o} resolution. The vertical coordinate system is based on sigma levels. In the latest version of NOGAPS the vertical resolution was increased from 24 to 30 levels (Figure 3). This change increases the number of levels below 850mb to nearly 6, dependent upon the terrain (Hogan et al., 2004).

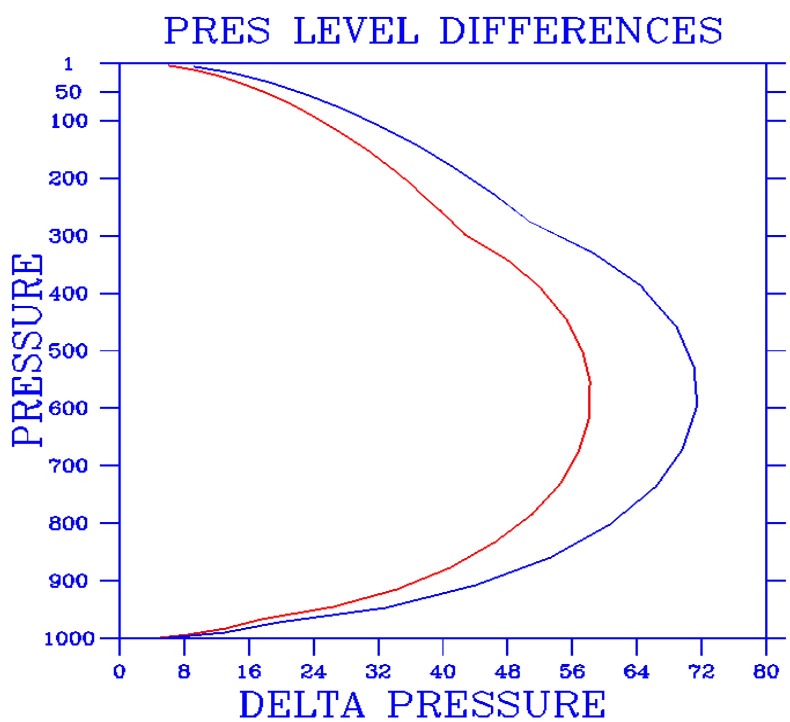

Figure 3. The pressure layer thicknesses (mb) versus pressure (mb) for the L30 (red) and the L24 (blue). The surface pressure is assumed to be 1000 mb.(From Ref. [Hogan et al., 2002]).

One particular advantage for NOGAPS, not generally found in other NWP models, is a three level cloud distribution. NOGAPS calculates cloud cover for low, medium, and high level in the atmosphere as a percent coverage. In the Arctic, this becomes important in the calculation of longwave flux from clouds to the surface. Models which include distinct low cloud parameterizations tend to handle the longwave flux better than those with only a complete cloud cover parameterization. Table (1) includes the parameters that NOGAPS uses in creating a forecast, and Table (2) is a list of additions since the upgrade of NOGAPS to version 4.0. Two features of NOGAPS, the cloud parameterization and the surface energy budget, are particularly important in polar regions and will be discussed in more detail.

a. Energy Flux Parameterization

Because SHEBA deals directly with the question of how the Arctic heat budget is controlled, it is important to know how the model handles the business of transferring energy between different locations. NOGAPS uses a longwave parameterization scheme from (Harshvardhan et al., 1987). The specifics of the parameterization are detailed in (Hogan and Rosmond, 1991). The shortwave parameterization is based on work by (Davies, 1982). Davies work was influenced by (Lacis and Hansen, 1974) and (Hogan and Rosmond, 1991).

Table 1. NOGAPS Basic Parameters (From Ref. [FNMOC Website, 11 August 2004]).

Basic equations:	Primitive equations with hydrostatic approximation
Independent variables:	Latitude, longitude, hybrid pressure coordinate, sigma levels
Dependent variables:	Vorticity, divergence, virtual potential temperature, specific humidity, surface pressure, ground temperature, ground wetness and cloud fraction
Numerical techniques:	Horizontal spectral differencing, second-order finite difference in the vertical, and central time differencing with Robert semi- implicit corrections
Integration domain:	Global, surface to 1 mb
Horizontal resolution:	T239 (~0.5 degree on the Gaussian grid)
Vertical levels:	30 sigma levels with approximately 6 sigma levels below 850 mb, depending on terrain elevation
Forecast time:	144 h from the 00Z, 06Z, 12Z and 18Z ops run
Initial fields:	Machenhauer initialization of increments from the U.S. Navy Atmospheric Variational Data Assimilation System (NAVDAS)
First-guess fields:	Previous NOGAPS 6-h or 12-h forecast
Orography:	Spectrally truncated and Lanczos filtered mean heights from the USGS Global Land One-kilometer Base Elevation (GLOBE) database.
Horizontal diffusion:	Linear, fourth-order LaPlacian for vorticity, divergence and temperature
Moisture physics:	Convective precipitation (Emanuel), shallow cumulus mixing (Tiedtke) and large-scale convection
Radiation:	Long-wave and short-wave radiation (Harshvardhan) computed every 2 hour
Gravity wave drag:	(Webster et al.)
Planetary boundary layer:	(Louis)
Land surface:	Single layer/bucket model
Ocean surface:	Sea surface temperature and ice coverage percentage from U. S. Navy NCODA.

Table 2. NOGAPS Dynamics, Parameterization and Operational Improvements Since 1998 (From Ref. [FNMOC Website, 11 August 2004]).

APR 1999	- Improve sea-ice latent heat release, resulting in slightly decreased evaporative flux
JUN 2000	- Replace the Relaxed Arakawa-Schubert cumulus parameterization with Emanuel cumulus parameterization
SEP 2000	- Increase stratospheric diffusion, resulting in reduced SH stratospheric jets
SEP 2000	- Implement higher resolution terrain fields from NIMA DTED Level 1 terrain database
DEC 2000	- Change cloud parameterization, better representing coastal and Arctic stratus, leading to reduced Arctic warm bias and increased tropical lower level winds
MAR 2001	- Improve vertical diffusion and Emanuel cumulus convection, better estimating initial heat flux and reducing upper level tropical temperature warm bias
MAY 2001	- Improve Emanuel cumulus convection, making the vertical profile of mixing cloud mass flux a function of buoyancy rather than buoyancy gradient, further reducing upper level tropical temperature warm bias
JUN 2002	- Update Emanuel convective scheme, adjusting specific heat of liquid-ice phase to reduce upper level heating, and selecting convection source level to maximize buoyancy at LCL, improving cloud base mass flux
JUL 2002	- Set a minimum snow depth for perpetually snow-covered regions (Greenland and Antarctica), to counteract the model tendency of melting off during extended absences of snow data
SEP 2002	- Increase NOGAPS resolution to T239/L30/0.5 degree
JUL 2003	- Convert NOGAPS from 64-bit to 32-bit, except for matrix inversion.
JUL 2003	- Improve matrix inversion module
SEP 2003	- NAVDAS data assimilation system operational
NOV 2003	- Implement terrain fields from USGS Global Land One-kilometer Base Elevation (GLOBE) database.
NOV 2003	- Change gravity wave drag scheme to Webster et al.

Even with continuous list of changes being made there will always be some model tendencies that are present. An up-to-date list is maintained by FNMOC on the website: https://www.fnmoc.navy.mil. Table (3) is the most current list of tendencies available at this time. These are not specific to the Arctic, but many of the items in Table (3) are relevant to the Arctic situation.

Table 3. NOGAPS Tendencies (From Ref. [FNMOC website, 11 August 2004]).

A. Surface lows

(ACPE = average central pressure error (bias). It is defined as the forecast central pressure minus the verifying analysis central pressure for each low being tracked. Negative ACPE indicates a bias toward being over forecast (deep); positive ACPE indicates a bias toward being under forecast or weak.)

1) Developing oceanic lows tend to be slightly under forecast and slow to deepen with an ACPE near zero through 72 hours. Mature, filling oceanic lows tend to be -2 to -3 mb over forecast and slow to fill.

2) NOGAPS tendencies for land and ocean basin surface lows are:

a) Atlantic developing low ACPE is slightly weak and slow to deepen by 48 hours. Atlantic mature lows are mostly deep and slow to fill. Filling low ACPE is -3 to -4 mb by 48/72 hours.

b) Pacific developing low ACPE is slightly weak and slow to deepen by 72 hours. Pacific mature lows are -3 to -4 mb deep and slow to fill by 72 hours.

c) In view of the general NOGAPS model tendency to under forecast oceanic developing SLP lows and over forecast oceanic mature, filling surface lows; associated surface wind speed forecasts also exhibit similar biases in the areas of higher wind speeds. Surface wind forecasts associated with deepening (filling) lows are under forecast (over forecast).

3) Former West Pacific tropical cyclones are typically slow to move during and after transition to extra-tropical.

4) Secondary cyclogenesis continues to be under forecast. Lee cyclogenesis off Southeast Kamchatka and Greenland is under forecast.

5) NOGAPS continues to merge complex lows into one, usually deeper low pressure system, especially at the extended forecast period.

6) Surface lows forming south of the polar jet under weak synoptic-scale forcing are slow to deepen.

7) Surface lows north of the polar jet at high latitude (>50N latitude) tend to be too deep. These are usually mature lows which have bottomed-out and tend to be slow to fill.

8) Sea-level pressure analyses and forecasts over the very high terrain of Greenland, Himalayas, and Antarctica are suspect and should be used with caution.

9) In the warm seasons, late Spring to early Fall, a spuriously deep surface low is observed in the analysis and forecasts over the very high terrain of the Himalayas (vicinity 30N-090E). This "lock-in" feature is caused by model reduction of station pressure to sea-level, and the warm season surface air temperatures.

B. Tropical cyclones

1) NOGAPS exhibits several model tendencies associated with a tropical cyclone's stages of evolution:

a) Tropical cyclone genesis: NOGAPS tends to generate spurious tropical cyclones in the extended forecast periods (tau 72 and beyond). This is most pronounced in the Indian and West Pacific Oceans.
b) Tropical cyclone phase: Due to the resolution of the NOGAPS global model, sizes of tropical cyclones in the NOGAPS analyses and forecasts are almost always too large in aerial extent and this may cause false interaction with nearby tropical cyclones.
c) Transition and extra-tropical phase: For tropical cyclones undergoing transition to extra-tropical, the forecast surface low is usually over forecast (deep), slow to fill, and slow to move. In the re-deepening extra-tropical phase, former tropical cyclones are under forecast (weak) and slow to move. Directional bias is usually behind and to the left of the analysis track (slow to move and toward the U/L cold air), especially is zonal flow.

2) Track errors: On average, NOGAPS TC forecasts tend to be east and south of the verifying position in a cartesian coordinate framework. In a storm-relative sense ("following the storm"), NOGAPS TC forecast are behind and to the left of the verifying position.

C. Upper-level:

1) Forecast upper level troughs and associated surface lows moving in strong zonal flow tend to be fast to move, especially at extended forecast periods.

2) Upper level highs south of the polar jet are slightly strong.

3) NOGAPS wind speed forecast variability is greatest in the 300 to 250 mb jetstream region of the upper troposphere. Intense jet level winds may be under forecast due to the limited vertical resolution of the model.

E. SHEBA

SHEBA was designed to collect data regarding the Arctic's complex energy balance near the surface to better understand how different parameters interact. The experiment was conducted over a year long period, from October 1997 through October 1998. Particular data collected during SHEBA included at least two rawinsonde launches daily, and continuous measurements of sensible heat flux, latent heat flux, solar radiance, outgoing/incoming longwave and shortwave flux, two meter air temperature, ten meter wind speed and direction, albedo, and cloud cover. Satellite imagery was compared with the measured albedo and cloud cover. In addition, there were aircraft data collections (Uttal et al., 2002).

II. DATA

A. MODEL DATA

Dr. Timothy F. Hogan from the Navy Research Lab (NRL) provided the model data required to complete this study. In addition, he provided extensive support with the processing of the data post model run. Hogan performed three special NOGAPS re-runs that included spring, summer, and winter periods. To limit the scope of this comparison, focus was on near-surface measurements, rather than the complete atmospheric column.

Each model run produced data for the entire globe, but these were filtered using the ship's time and position to obtain a single horizontal data point representing the SHEBA location. In addition to filtering the time and position, the data set was limited to only particular variables of interest (Table 4).

Table 4. NOGAPS variables provided by NRL for comparison against the SHEBA data set. Not every variable had a comparable value from the SHEBA data collection.

Julian Date
Forecast Hour
Latitude
Longitude
Sea Ice Concentration
Sea Level Pressure
Terrain Pressure
Sea Ice Temperature
Two Meter Temperature
Sensible Heat
Latent Heat
Surface Longwave Flux
Surface Solar Flux
Outgoing Longwave Flux
Top of Atmosphere Solar Flux
Surface Dewpoint Depression
Total Precipitation
Total Precipitable Water
Total Cloud Fraction
Low Cloud Fraction
Middle Cloud Fraction

High Cloud Fraction
Ten Meter U Wind
Ten Meter V Wind
Ten Meter U Drag
Ten Meter V Drag

Using the latest release of NOGAPS, with T239 wave resolution, the model was able to produce data at a 0.5 degree resolution, and using an interpolation method NRL was able to construct a data set of values for the variables at the precise in-situ data collection location. This made comparison between SHEBA and NOGAPS relatively straightforward, as long as variable units were the same.

The model was initialized from an archived national database of meteorological measurements from six hours previous to the actual model run. Although the model predictions extended for several days in some cases, this thesis will examine only forecasts for the initial 24-hour period. This was to focus primarily on the physics behind the model rather than the errors produced and amplified within the model. Each of the parameters in Table (4) were calculated for each 6-hour increment starting from the model initialization and going out to 24 hours. The hope was that by focusing on a relatively short time prediction, it would be easier to evaluate specific physical processes in NOGAPS.

For each of the three periods of interest there were approximately 120 model runs. Each had a minimum of 5 forecasts for a total of over 1500 forecasts for the three periods with over 300 forecasts per forecast hour. This suggests that the sample size for the statistical methods can use a sample size of (N) vice the (N-1) methods. This was done for each of the variables in Table (4).

B. ARCTIC DATA SET

1. SHEBA

SHEBA represents the accumulation of approximately one year worth of data from a floating meteorology station. SHEBA was focused on the heat budget for the Arctic, and looked at many aspects of the atmosphere. Data from the three model run time periods were separated from the entire data set.

The ice camp station's position was recorded using the global positioning system (GPS). Temperatures were collected at both the ten and twenty meter towers. The ten meter winds were collected at the ten meter tower. The sensible and latent heats were collected at the station's twenty meter tower site. The shortwave and longwave fluxes were measured in the upward and downward facing directions by Eppley radiometers. The net fluxes were calculated using these measurements (Uttal et al., 2002).

The errors associated with the measurements were relatively small. For temperature the tower measurements were within 0.05 K except during periods when high levels of frost had accumulated. The longwave components had errors in the range of -1.0Wm^{-2}, while the shortwave error was on the order of -2.6 and -2.2Wm^{-2} for the incoming and outgoing fluxes respectively. A complete list of errors and biases from the SHEBA measurements can be found in Table (5) of (Persson et al., 2002).

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III. DATA PROCESSING

A. FORTRAN CONVERSION

The complexity of a NWP requires a great deal of programming to manipulate the equations governing the processes being modeled. In the case of NOGAPS, FORTRAN has been the programming language of choice since 1982. FORTRAN has been the most popular method for coding mathematical operations. This is a concern since the files that were exported from NOGAPS were FORTRAN files and to get to a useable form required conversion on a UNIX based machine at the Naval Postgraduate School (NPS).

NRL provided the program required to decompress the data into text files. These text files were then edited to remove extraneous text for loading into Matlab. Modifications to the program received from NRL were needed to output the data to a file with the proper naming convention for the subsequent Matlab m-files to process. Each FORTRAN file was converted individually to ensure data errors did not occur in the conversion.

B. MATLAB CODING

The text files produced by FORTRAN were grouped into seasons based on model run time. There were three Matlab programs used to convert and group the model output text files into useable databases. There was a fourth program used to take the SHEBA data files and create databases of that separate data.

The first program input the text files and removed the extraneous text from the text files and fills the subsequent database with the actual data. The second program used the newly created data and produced time series plots of the data. It also took the SHEBA output data from the fourth program and combined them with the plots from the model. In addition the fourth program added a line of data to the database matrix. The model output incorporated six hour time steps, while the SHEBA data had one hour time steps. The fourth program stripped off every 6^{th} SHEBA data point, and added it to the matrix at the correct time step with the model. The third program took the new data sets and performed the statistical calculations. The caveat to this last program was that the

standard deviation and mean for the SHEBA data sets were calculated using the entire one hour time step data, so as to not lose resolution in their calculation.

C. DATA EVALUATION

For the model data, no filtering took place, with the exception of the ten meter winds. The model output separated the ten meter winds into u and v components. To match the SHEBA data set these two components were combined to produce a single wind vector. Only the magnitudes of the ten meter wind components were used in the comparison.

In both cases, all temperatures were converted to Kelvin, all fluxes had units of Wm^{-2} and dates were converted to a Matlab friendly format using the 'DATENUM' function. This allowed the easiest straightforward method for merging the two data sets together. In each period the difference between the model forecast and the actual SHEBA data was calculated.

1. Differencing

The focus of looking at the differences between the forecasted quantities and the actual measured values is to identify trends in the error of the model. It is a simple method that looks at each data pair and subtracts the actual data from the forecast. This establishes a trend for model errors.

$$DIFFERENCE = FORECAST - OBSERVATION$$

A difference for each of the forecasts from the analysis to the 24 hour forecast are included to compare the differences between the different forecast hours.

D. STATISTICAL CALCULATIONS

1. Bias

Bias describes systematic differences over a period of time. Looking at the difference between the forecast and the observed data as a function forecast time reveals consistent error trends. In the case of the SHEBA data, each six hour data point was compared to the model analysis, six, twelve, eighteen, and twenty-four hour forecast. The individual differences were combined together and averaged by the total number of data point pairs to find the bias values for each forecast hour. The following equation

was used to calculate the bias using Matlab. The equation was set such that a positive value correlates to the model data value being larger than the observed data.

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)$$

2. Standard Deviation (SD)

To be able to compare the model output to the SHEBA data, a baseline of performance must be established. The simplest baseline is to compare results from the model against the standard deviation of the SHEBA variable. For each variable, a standard deviation was calculated, using the following equation. Table 5 contains a list of each variables standard deviation for the three periods.

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - \bar{O})^2}$$

Variable	SHEBA
Sea Level Pressure	11.5 Wm^{-2}
Sensible Heat Flux	9.5 Wm^{-2}
Longwave Flux	21.3 Wm^{-2}
Solar Flux	44.8 Wm^{-2}
10m Wind Speed	2.5 ms^{-1}
2m Temperature	13.0 K
Surface Temp	13.8 K

Table 5. Standard deviation of the SHEBA data variables for entire SHEBA period (October 1997 to October 1998).

To compare against the standard deviation a root mean square difference was calculated for each of the NOGAPS variables for each period.

3. Root Mean Square Differencing (RMSd)

The RMSd is a measure of the mean difference between the forecast (F_i) and observation (O_i). It implicitly includes the bias term, so the bias of the forecast will

adversely affect the RMSd value. If the forecast is relatively close to the observation the RMSd will be relatively small.

$$RMSd = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2}$$

4. Standard Error (SE)

To determine if there is any significance to the bias calculation a standard error of the SHEBA data was calculated. By combining the standard error to the bias, any significance to a trend can be validated. If the standard error suggests the bias could be nearly zero, then there would be little reason to believe the model was not performing adequately. However, if the bias is larger than the standard error, this would suggest the model had a significant bias trend in its data.

$$SE = \sqrt{\frac{1}{N^2}\sum_{i=1}^{N}(O_i - \bar{O}_i)^2}$$

IV. ANALYSIS AND RESULTS

There are several features that are important to the comparison of the data sets. Is there any persistence of the model towards one particular solution? Did the model over-predict (under-predict) the forecast? Was the forecast trend accurate but with bias errors? Each week has specific features that are worth noting. These issues deal with the efficiency of the model to deal with the balancing of the surface energy budget.

Since the terms in this study do not all follow the same sign convention in regards to what is positive and negative, they were all converted in the Matlab programs such that positive terms indicate surface heating. As an example, by convention the longwave flux is considered to be positive in the upward direction. The net longwave flux is generally positive since the outgoing longwave flux is generally larger than the incoming longwave flux. However, this would be indicative of surface cooling. This did not make for ease in understanding the graphs, so the signs for these types of fluxes were changed to make it easier to understand the graphs. The exception to this rule was the solar flux which is positive downward, and did not require any sign modifications.

A. WINTER DATA SET

The winter data set was collected from December 1997 to January 1998. The lack of solar input was the major factor to note in the winter data set. Because the winter lacks any solar input, the net longwave flux and temperature advection are particularly important for determining temperature changes. The Arctic winter atmosphere is extremely dry, which allows more longwave energy to escape through the atmosphere. Cloud cover is at a minimum with the dry atmosphere, and with the extremely cold temperatures the surface emits energy at longer wavelengths than the standard atmosphere.

1. Sea Level Pressure (SLP)

Initial model analysis pressures are virtually identical to SHEBA because the latter were incorporated into most of the model runs. The initial time series plots of the SLP (Figure 4) do not reveal significant insight to the model performance. It is apparent

that there are diversions in the extended forecasts at certain times, but for most of the initial forecasts in the first 24-hour period there is a close correlation of the model to measured data.

Looking at the bias (Figure 5) there is a tendency for the SLP to have a slight negative bias of 0.7 mb compared to the measured data over the forecast hours. The plot of the difference shows that the largest error was nearly 4 mb on the 4th of January. For a majority of the time the error did not exceed 2 mb in either the positive or negative direction. Lastly the comparison of the RMSd values for the forecast hours versus the standard deviation of the SHEBA data suggests that the model did better than the natural variability of the data.

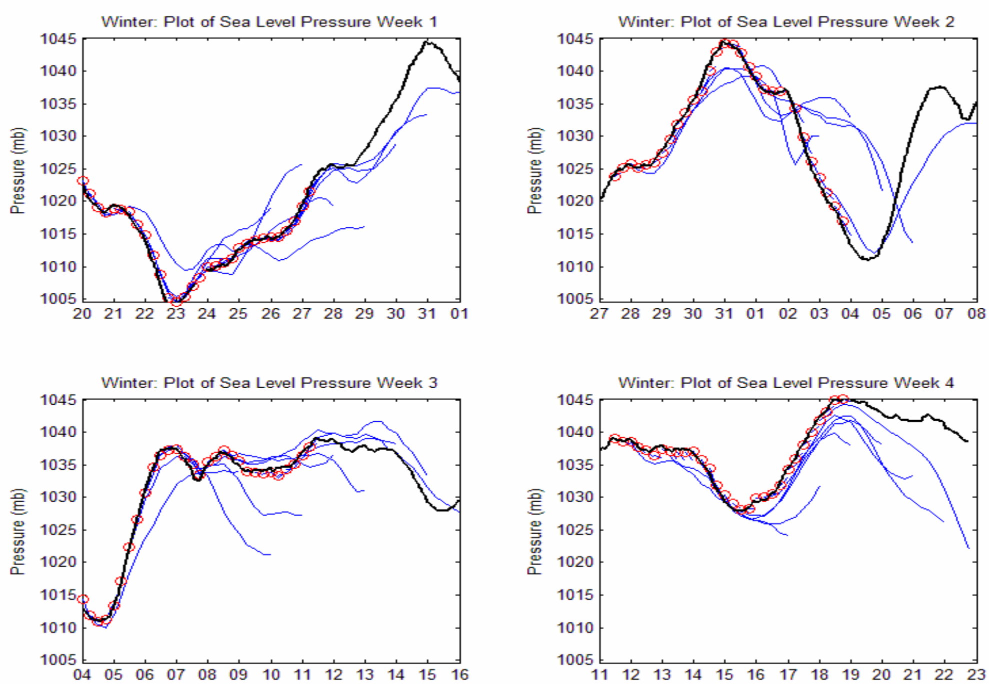

Figure 4. Sea level pressure for winter period. The red circle represents the model analysis and the blue lines represent the forecasts for the analyses from which they originate. The thicker black line is the available SHEBA data. Each week of the observations was separated in the plot to make interpretation easier and to bring out the smaller details lost in a single plot of the complete data set. There are several days of overlap at the end of each week to view entire forecast.

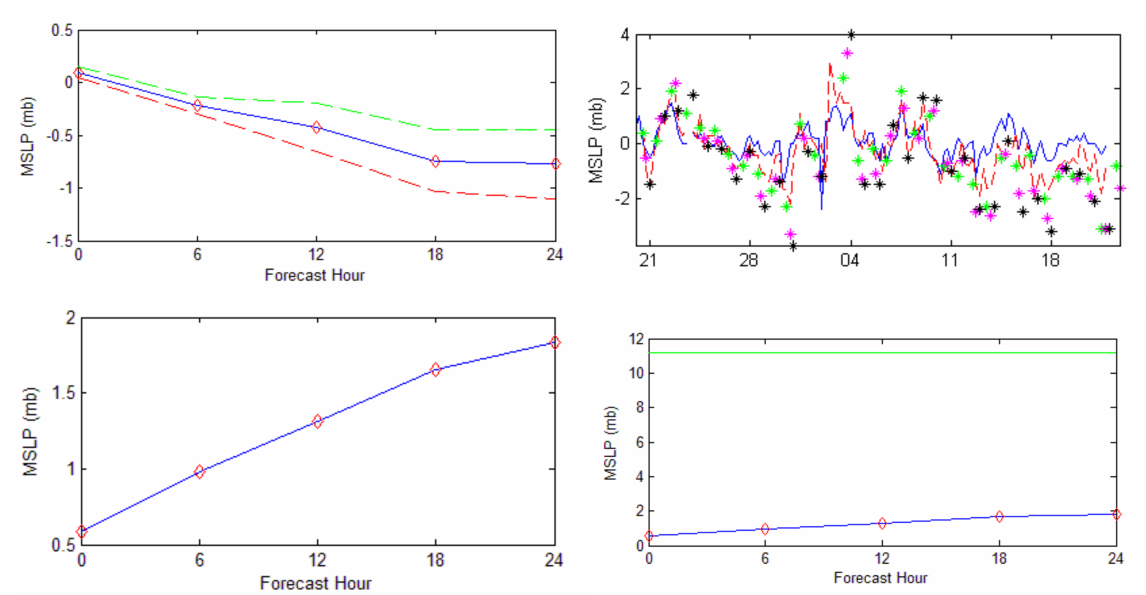

Figure 5. Winter SLP plot of bias, differencing, RMSd, and standard deviation comparions. The upper left plot is the bias. The blue line with red diamonds is the calculated bias and the dashed green and red lines are the standard error calculated for the period. The upper right plot is the differencing. The blue line is for the analysis, the red dashed line is the six hour forecast, the green stars are for the twelve hour forecast, the magenta stars are the eighteen hour forecast, and the black stars are the twenty-four hour forecast. The lower left plot is the RMSd, to look at details of the RMSd. The lower right plot is a comparison of the RMSd versus standard deviation. The blue line with red diamonds is the calculated RMSd and the green line is the standard deviation of the SHEBA data.

2. Sensible Heat Flux

During the winter season there is a tendency for the net sensible heat flux to be positive (heating the surface) to replace the heat lost from the longwave radiation. In general the model was unable to pick up on this because the surface temperature was too warm.

There were several voids in the SHEBA data, due to instrument icing, the first at the start of the week and the second between the 25th and 27th, the third between the 31st and 2nd, and fourth from 5th to 7th (Figure 6). Week one data reflects a previously mentioned event on the 22nd that has led to an increase in the sensible heat flux. The model data has a tendency to have too much cooling taking place. The second week

starts out with the model forecasting a sensible heat flux near zero, while the data still reflects warming taking place. From the 3rd through the rest of the week there appears to be some correlation between the two data sets. There is a noticeable decrease in the SHEBA data set to a negative flux of 10 Wm^{-2} on the 3rd. The third week has significant correlation between the two data sets, but there is a large oscillation in the SHEBA data. The last week of data again shows the model shows less surface warming than SHEBA over the entire week.

The sensible heat bias (Figure 7) shows that the model was cooling faster by an average of 7 Wm^{-2}. The RMSd trend starts out at 11Wm^{-2} but decreases over the 24-hour forecast period to 8 Wm^{-2}. Looking at how this compares to the standard deviation, the model does not fair well for the entire twenty-four hour forecast period. There is some improvement after the first fifteen hours but never gets below the standard deviation. The decrease in RMSd appears to suggest the model has an initial imbalance that after the twenty-four hour period is partially corrected.

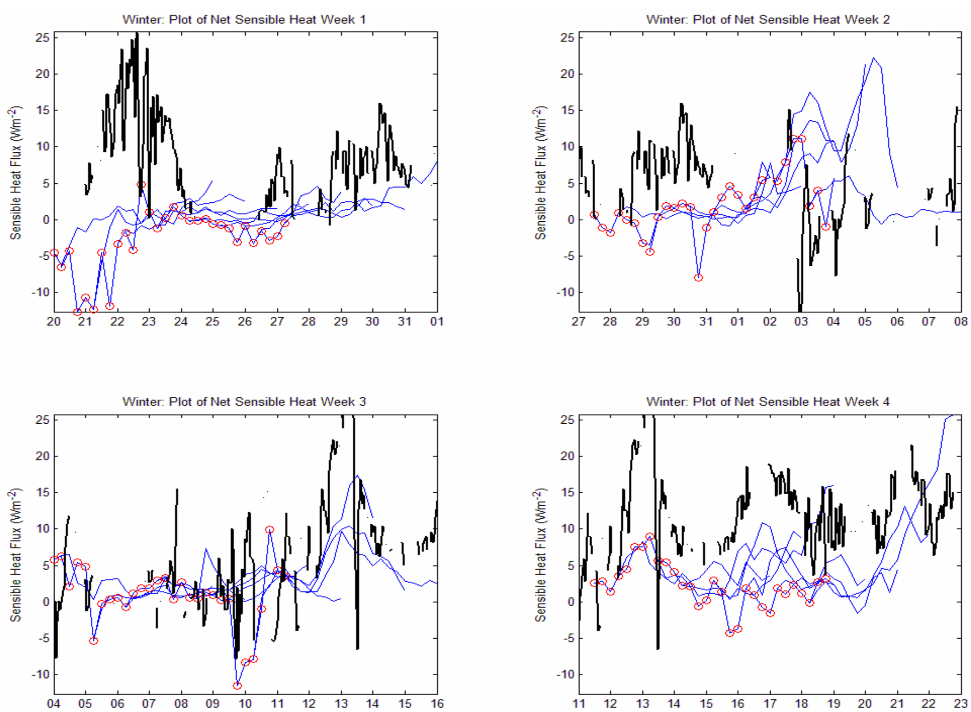

Figure 6. Sensible heat flux for winter period. Representation is similar to figure (4).

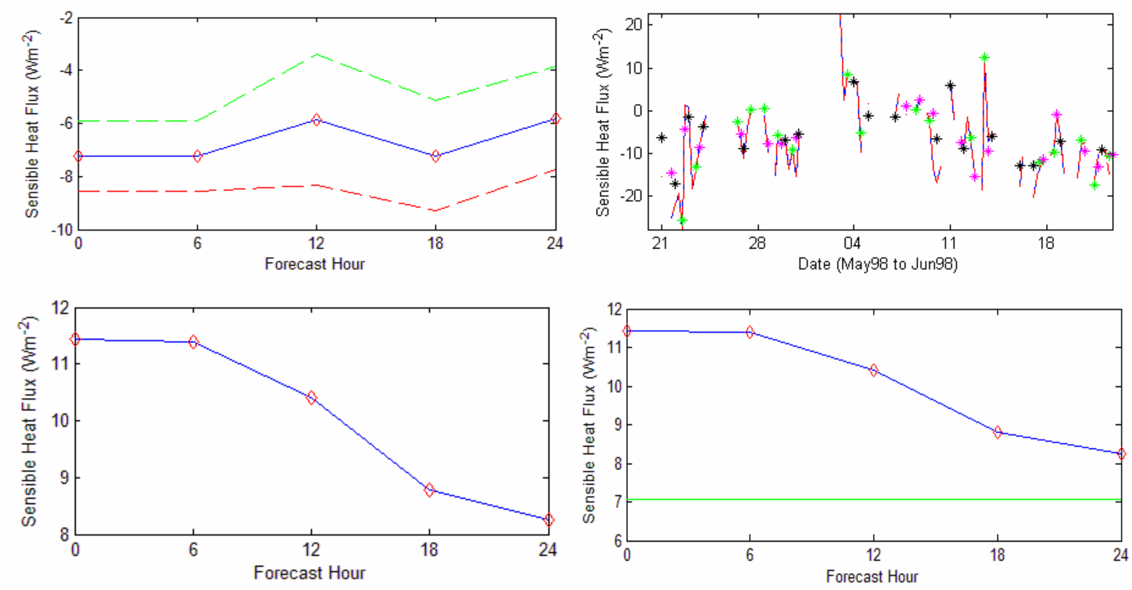

Figure 7. Winter net surface sensible heat flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

3. Longwave Flux

The longwave flux (Figure 8) shows dramatic differences between the two data sets. The modeled longwave flux cools the surface much more than the SHEBA observations, as the difference is as large as 60Wm^{-2} between the two data sets. The bias shows this large cooling difference for the forecasts is around -30Wm^{-2} for the individual forecast hours. This indicates considerable disagreement and is reflected in the RMSd comparison to SHEBA's standard deviation (Figure 9) with the RMSd being well above the standard deviation. This is mostly due to the significant difference between the model and SHEBA surface temperature, which will be discussed below.

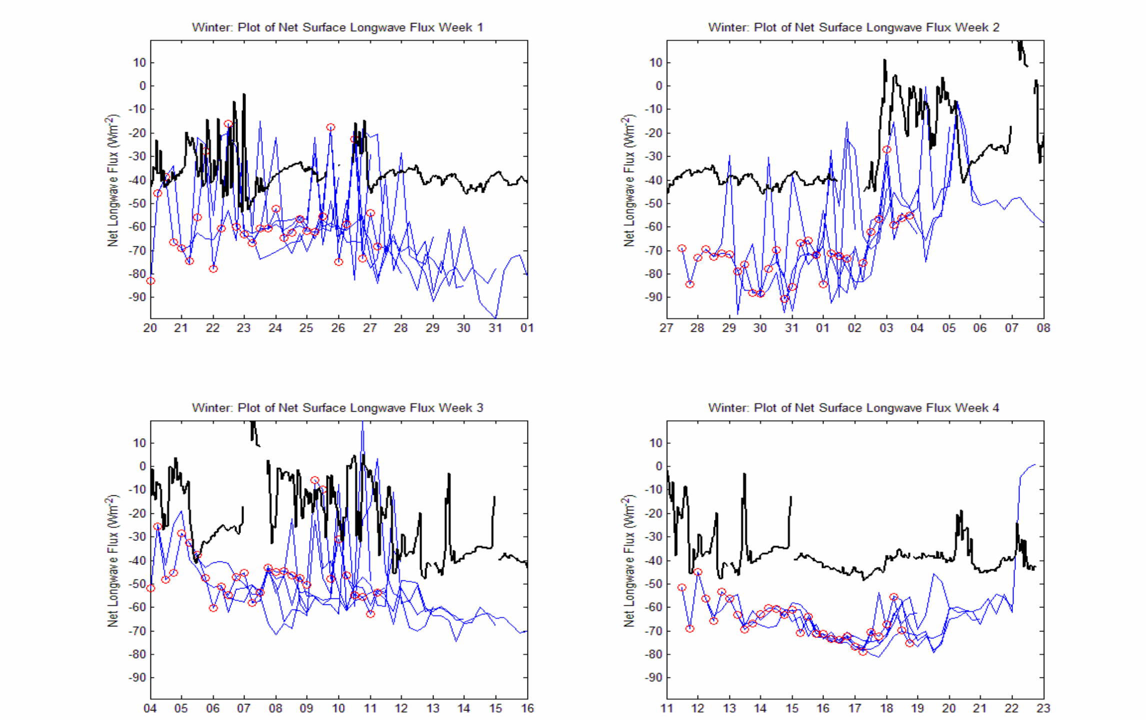

Figure 8. Net surface Longwave Flux for winter period. Representation is similar to figure (4).

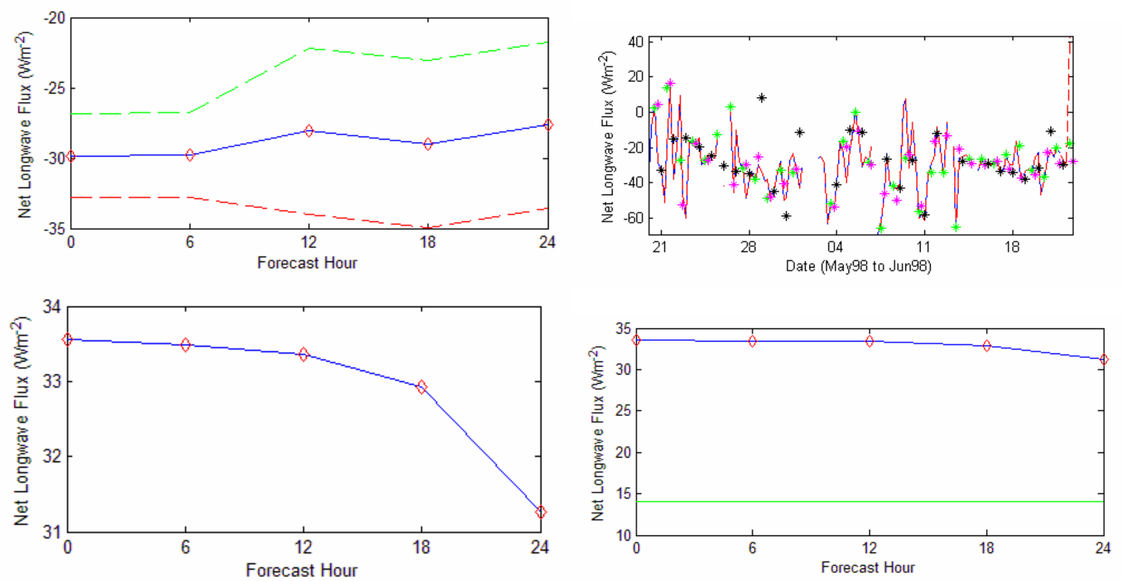

Figure 9. Winter net surface longwave flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

4. Solar Flux

The solar input during the winter period is zero at the latitude of the SHEBA site, therefore no data are shown. There were no inconsistencies in the SHEBA data that suggested a sensor might be working improperly. The sensors used during SHEBA showed zero shortwave radiation readings for the entire winter period.

5. Ten Meter Wind Speed

The ten meter wind speed analysis calculated by the model has significant correlation with the SHEBA data (Figure 10). Similar to the sea level pressure, it appears that the ten meter wind speed has been added as a part of the data archive used to initialize the model. The forecasts show skill in being able to accurately predict change in the short term. The extended forecasts appear to over-forecast the wind speed, but there are no errors larger than 5 ms^{-1} in any of the plots.

The bias (Figure 11) does not show any significant model bias and the RMSd comparison shows the model has a good handle on the ten meter winds.

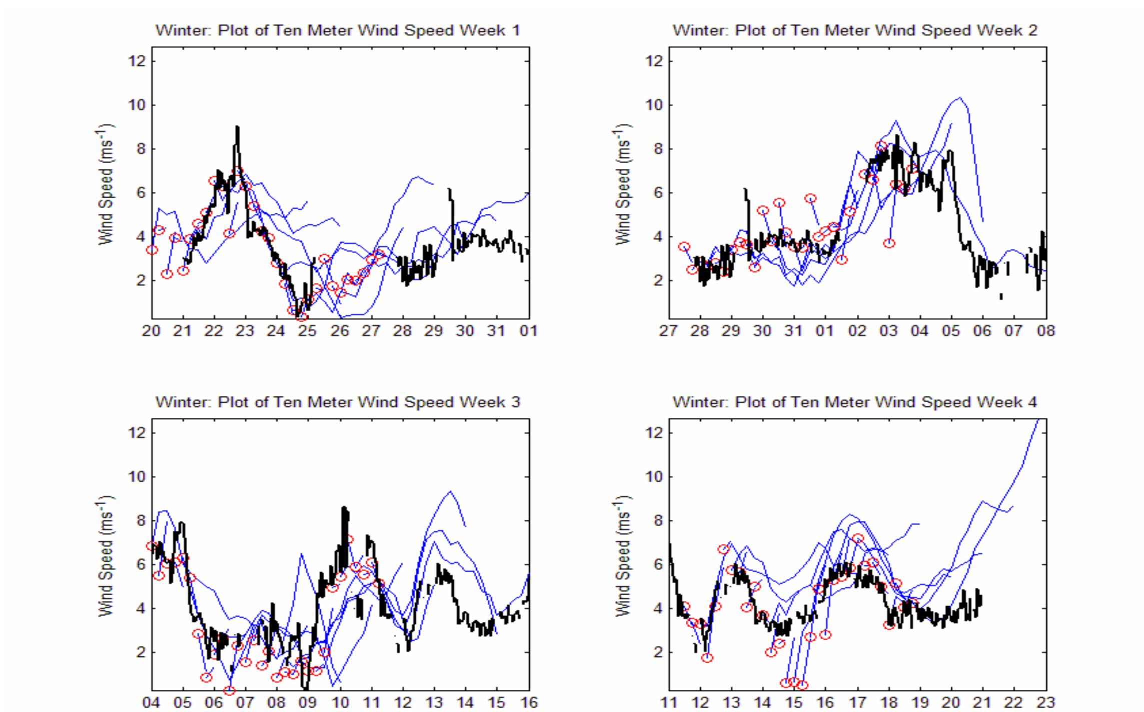

Figure 10. Ten meter wind speed for winter period. Representation is similar to figure (4).

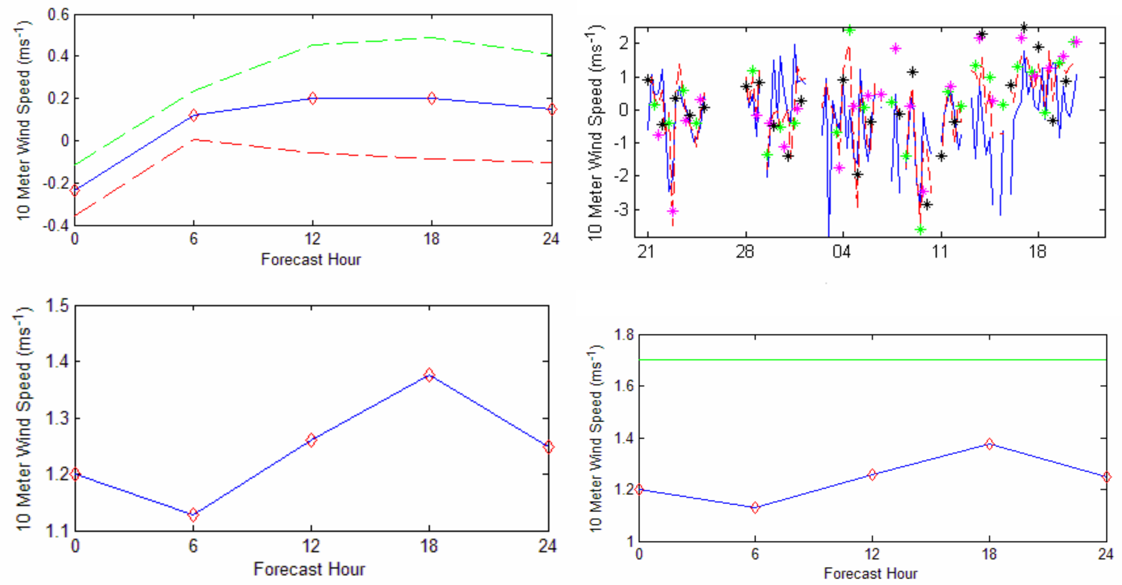

Figure 11. Winter ten meter wind speed plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

6. Two Meter Temperature

The predominant feature of the two meter temperature is that the model has very little fluctuation from the 245 K value (Figure 12). In the first week there is a pattern of the model initializing in the low 240 K range and increase to 245 K by the end of the forecast period. The model shows a weak oscillation (only 2-3 K) over the four week period. The SHEBA data had more variability, showing several warming and cooling periods. In the first week, the temperature shows signatures of the event between the 22nd and 23rd discussed previously. During the event the air temperature increased approximately 15 K. For the next week there is a gradual cooling until the 1st, when there is a loss of data. Once the data continues there is another heating event that begins to take place. The temperature again increases about 15 K. From the end of the second week through the entire third week the temperature continues to remain high, fluctuating from 245 to 253 K. The next cooling event occurred around the 11th, and continued through the fourth week, with temperatures remaining near 240 K.

The bias shows the model has a 4-5 K temperature difference for the 24-hour forecast period. The RMSd for the two meter temperature is greater than the standard deviation at all forecast times (Figure 13). The small variability of NOGAPS's temperatures leads to the large differences between itself and SHEBA as the SHEBA data fluctuates largely around the NOGAPS value (Figure 12). A common occurrence present in all the temperature figures for each season is the tendency of the model to initialize and then seek a particular value. An example is in the first week of data all the initializations are below the 245 K temperature. In all the cases, after the initialization the forecasts go to the 245 K temperature. This is the case in each season, but the temperature mark is different for each.

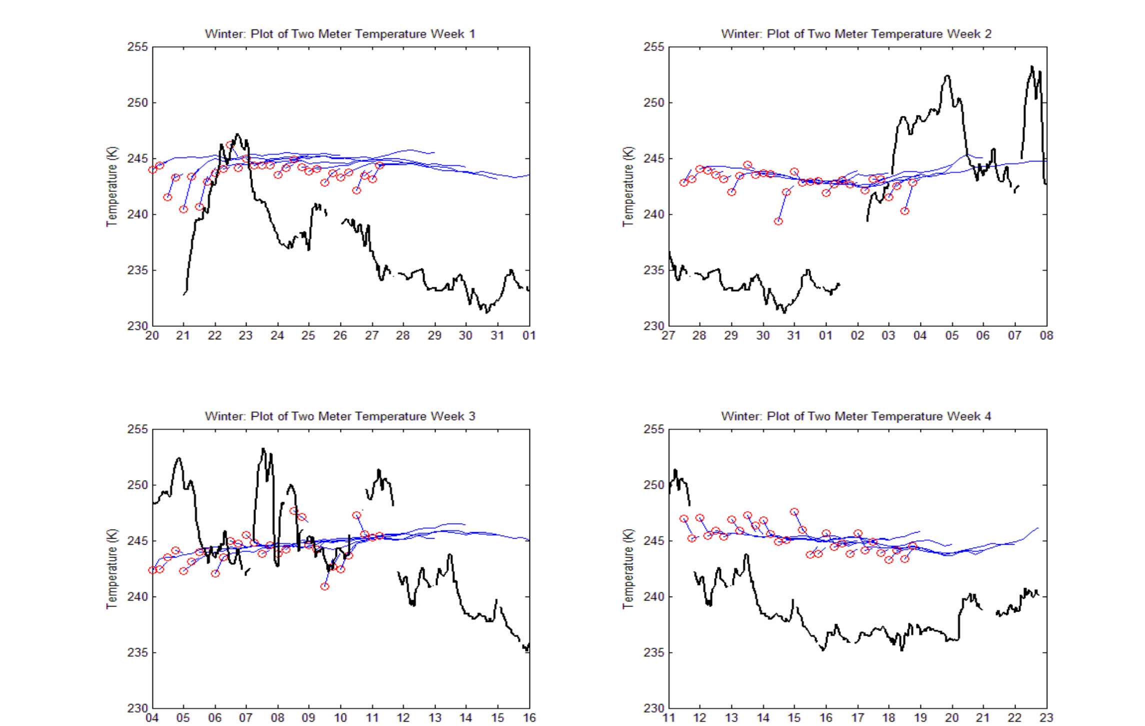

Figure 12. Two meter temperature for winter period. Representation is similar to figure (4).

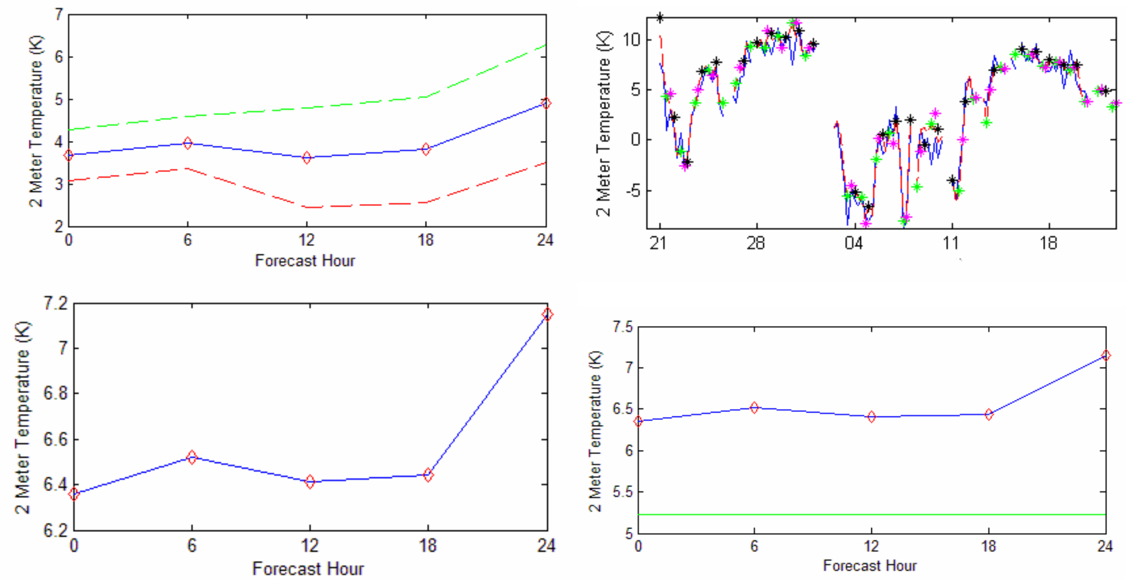

Figure 13. Winter two meter temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

7. Surface Temperature

The patterns seen in surface temperatures are very similar to those seen in the two meter temperatures. The model is again showing a damped oscillation over the four week period around 245 K. Looking at the comparison of the two meter temperature model analyses (Figure 12) to the analyses from the surface temperature (Figure 14) there is more variability in the range of temperature at which the model initialized. In both sets the analyses are seen to converge to a particular temperature, with the surface temperature being slightly warmer than the two meter temperature. The small variability in the model's temperature is one of the key findings in this paper. Looking at the bias (Figure 15) there is a significant positive trend. In addition the RMSd is well above the standard deviation for the SHEBA data. It has a large impact on the fluxes seen in the previous sections.

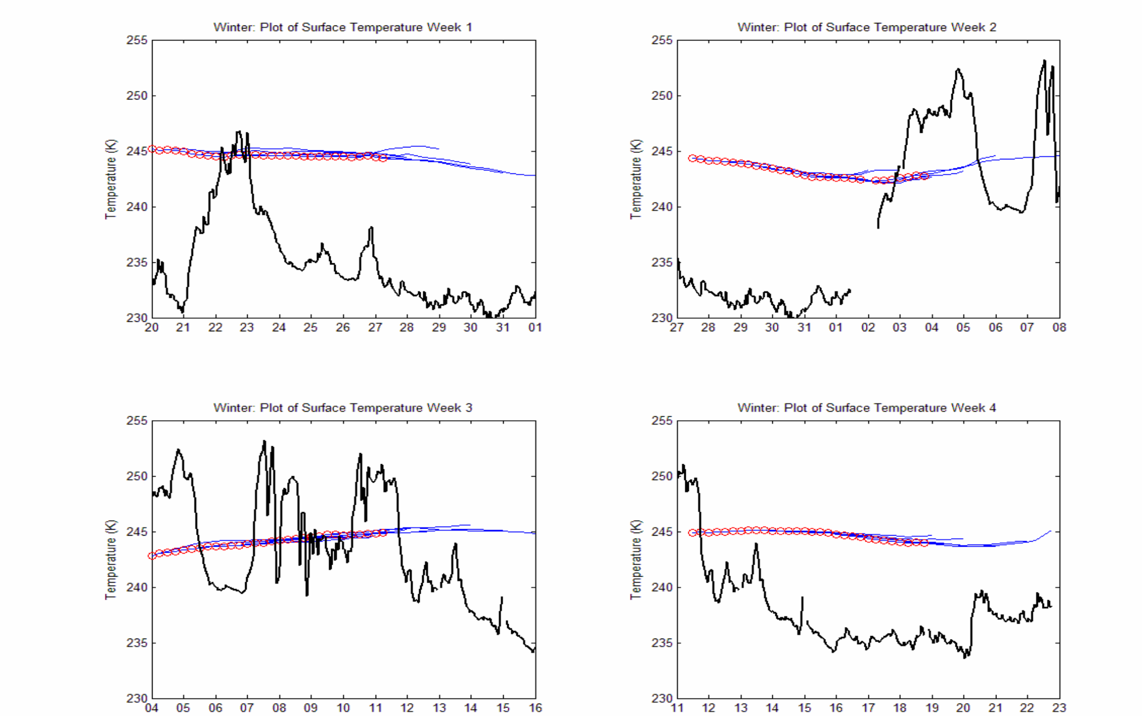

Figure 14. Surface temperature for winter period. Representation is similar to figure (4).

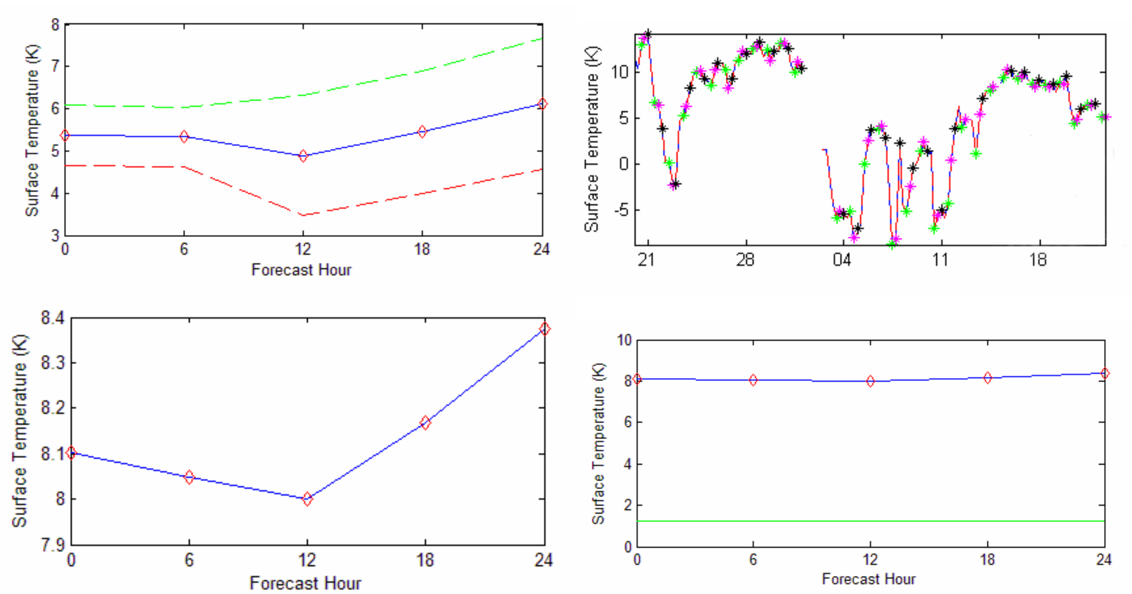

Figure 15. Winter surface temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

8. Low Cloud Fraction

One of the major factors that contribute to the energy balance is the presence of clouds, and their distance to the surface. In NOGAPS there is a calculation for the low level clouds (below 750 mb). The plots of the low level cloud percentage (Figure 16) show that the model has a trend to initialize at nearly fifty percent. In addition there is a tendency for the model to forecast a decrease over the forecast run. The range of percentage tends to fluctuate from nearly zero to the fifty percent, for the model. This is a large change from the observed clouds. Those are not illustrated in this thesis, but follow a bi-modal distribution, i. e. it is usually either totally overcast or totally clear.

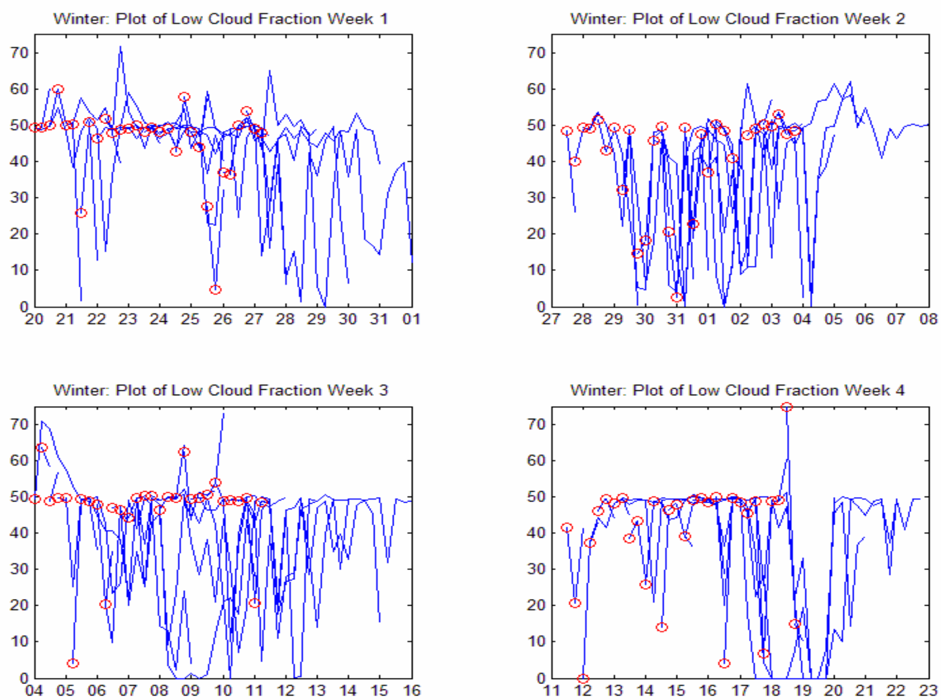

Figure 16. Low cloud percentage for winter period. Representation is similar to figure (4) except there is no SHEBA data plotted.

B. SPRING DATA SET

The spring data set was collected from May 1998 to June 1998. Similar to the winter analysis, the following figures are a combination of the two data sets. The distinctive feature for spring is the large diurnal variation of the surface temperature due to a varying solar flux and a dry snow covered surface that quickly changes temperature in response to forcing changes. Unlike the other seasons, the sun is reaching its minimum zenith angle and the lack of significant cloud cover creates the situation in which maximum solar energy can reach the surface. Snow covered surfaces have a rapid response in temperature to the availability of solar energy due to low thermal conductivity and low thermal capacity (storage). Assuming the model has a good handle on the input of solar energy, there should be very little change in the bias from one hour to the next.

1. Sea Level Pressure

The sea level pressure for the spring period has many of the same features seen in the winter set. The first feature is the tight correlation between the SHEBA data and the model initializations (Figure 17). Another feature is that there is the same tendency of the model to predict highs that were too weak and lows which did not deepen enough. In week one the model does an exceptional job of forecasting until the 14^{th}. From the 12^{th} until the 16^{th} the model under-forecast a high that came through the area. The model showed signs that the high on the 15^{th} would stop building at approximately 1015 mb and begin to decrease. It is quite apparent in the second week that the high continued to build to 1035 mb. In the second week the model runs continued to under-forecast the high. For weeks three and four there was good correlation between the forecasts and the SHEBA data. Of particular note is the small increase in pressure on the 28^{th}, from week three, that the extended forecasts from the previous days were able to pick up on fairly early. The statistical plots (Figure 18) have the same patterns observed in the winter period for SLP.

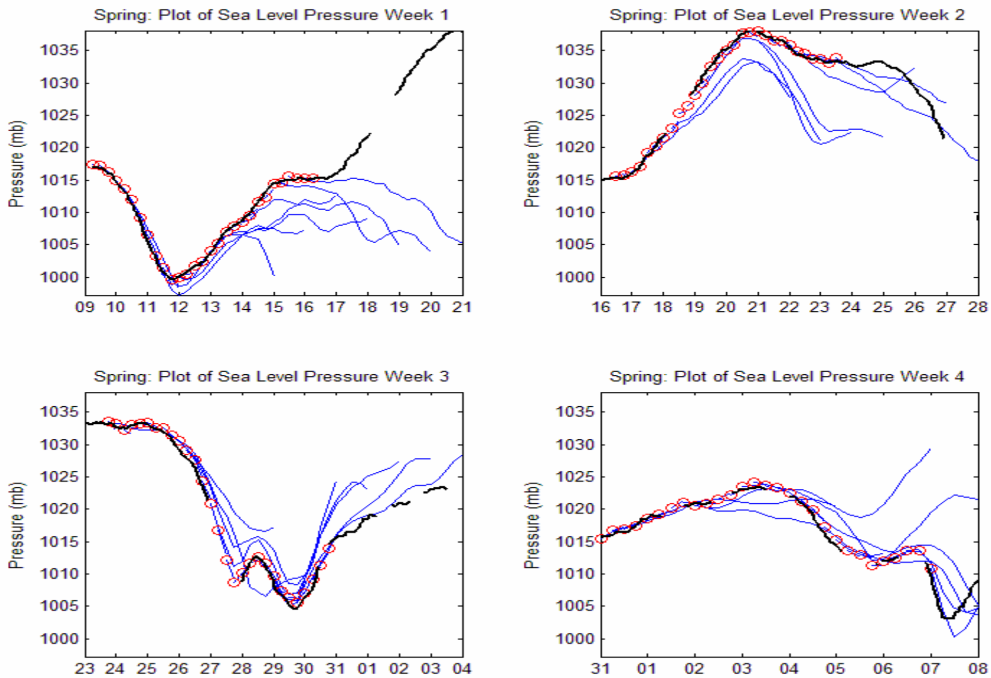

Figure 17. Sea level pressure for spring period. Representation is similar to figure (4).

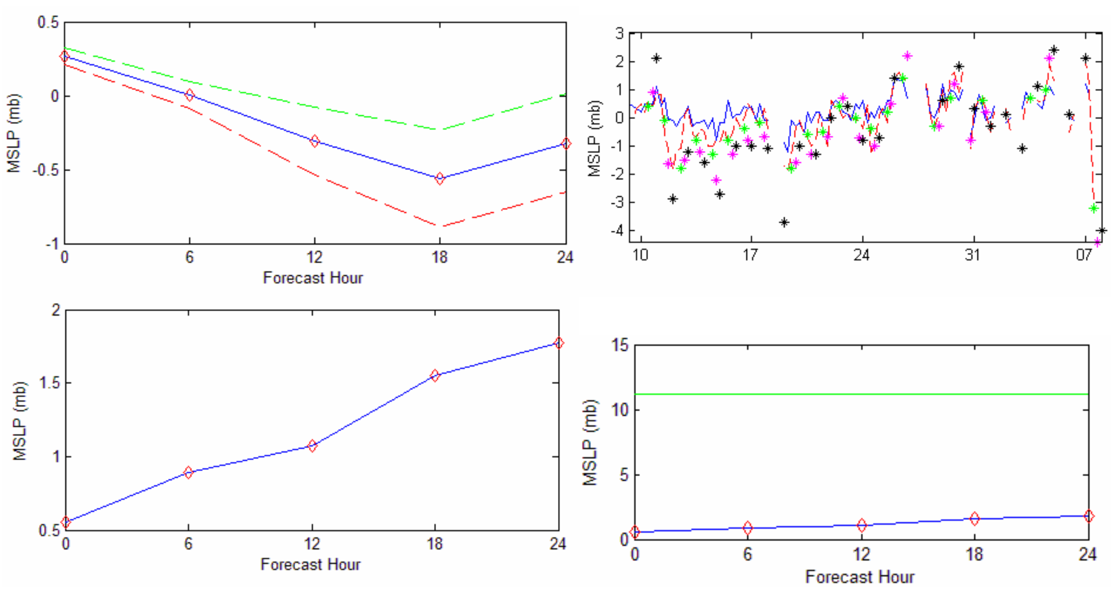

Figure 18. Spring sea level pressure plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

2. Sensible Heat Flux

The SHEBA data set appears to be diurnally influenced, with large variations from -20 to 20 Wm^{-2} changes over a single day (Figure 19). The model shows some indications of diurnal variations, but not nearly as much as the SHEBA data. In the second week there is a large shift in the SHEBA data on the 23rd and the model forecasts continue to increase, until the 28th. On the 28th the two data sets begin to show some correlation.

In the initial twelve hours of the forecast the model appears to have a bias near zero (Figure 20) but begins to show a positive bias from the twelve hour forecast through the twenty-four hour forecast. Comparing the RMSd to the standard deviation of the observations, the model was greater by 2-7Wm^{-2}, indicating a lack of model skill.

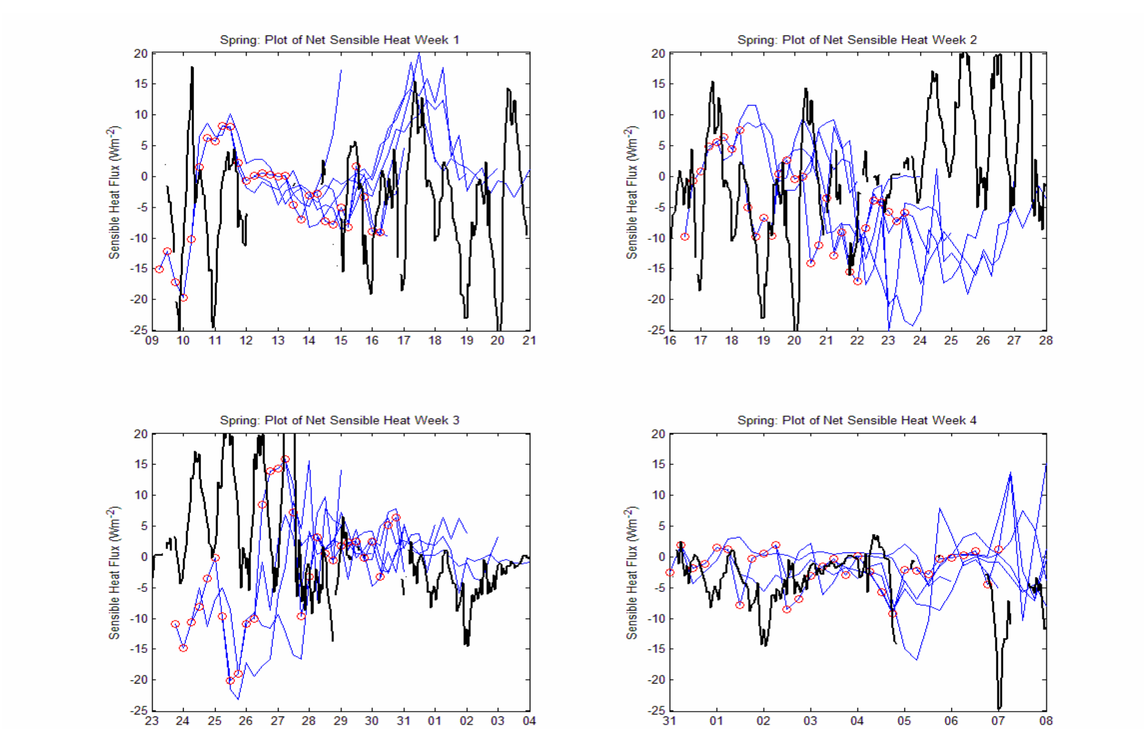

Figure 19. Net surface sensible heat flux for spring period. Representation is similar to figure (4).

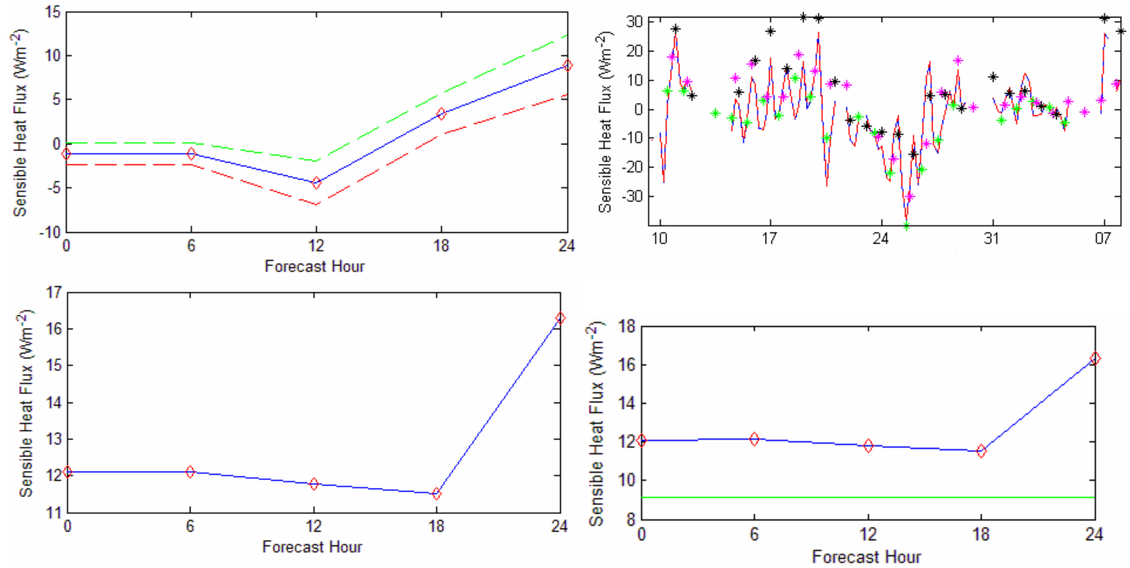

Figure 20. Spring net surface sensible heat flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

3. Longwave Flux

The longwave flux's appearance for the spring is similar to that of the winter. The same pattern of spikes between the -10 and -80 Wm^{-2} level is indicative of the bimodal cloud pattern seen in the Arctic. These shifts occur in as little as a single hour due to changes in cloud cover (Figure 21). There is no discernable correlation between the model and observations for the spring period.

Longwave radiation is highly dependent upon cloud cover which explains the rapid changes seen in the data. Periods in which the net longwave flux is nearly zero signifies a period when clouds were present overhead. Clouds act as an insulating layer and keep the surface from radiating energy away resulting in a cooling surface. During the spring NOGAPS had longwave biases in the range of -15Wm^{-2} (Figure 22). The RMSd values were well over the observed standard deviation.

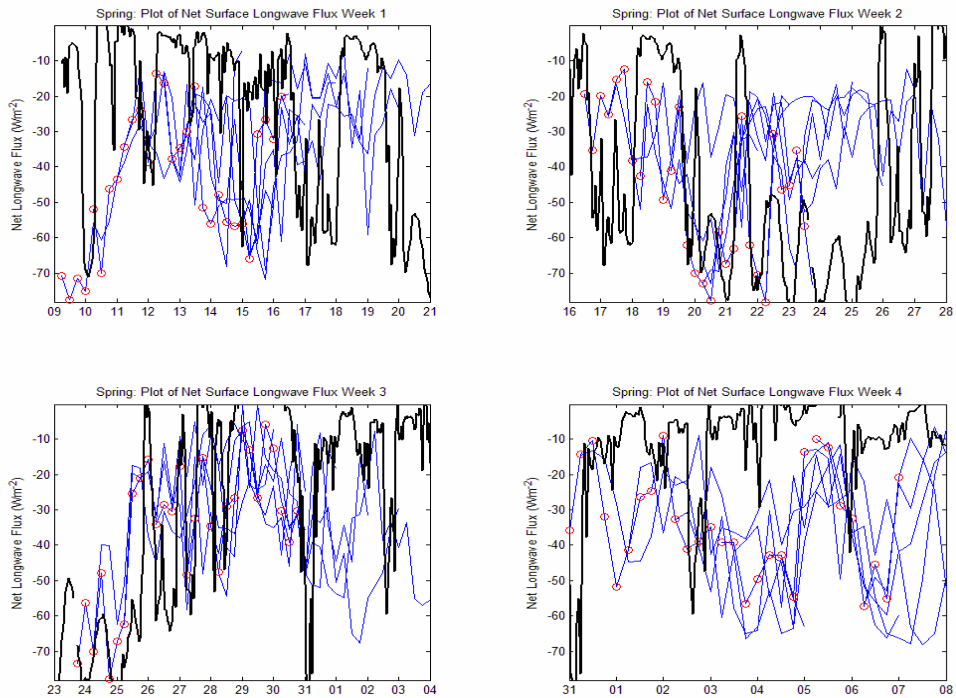

Figure 21. Net surface longwave flux for spring period. Representation is similar to figure (4).

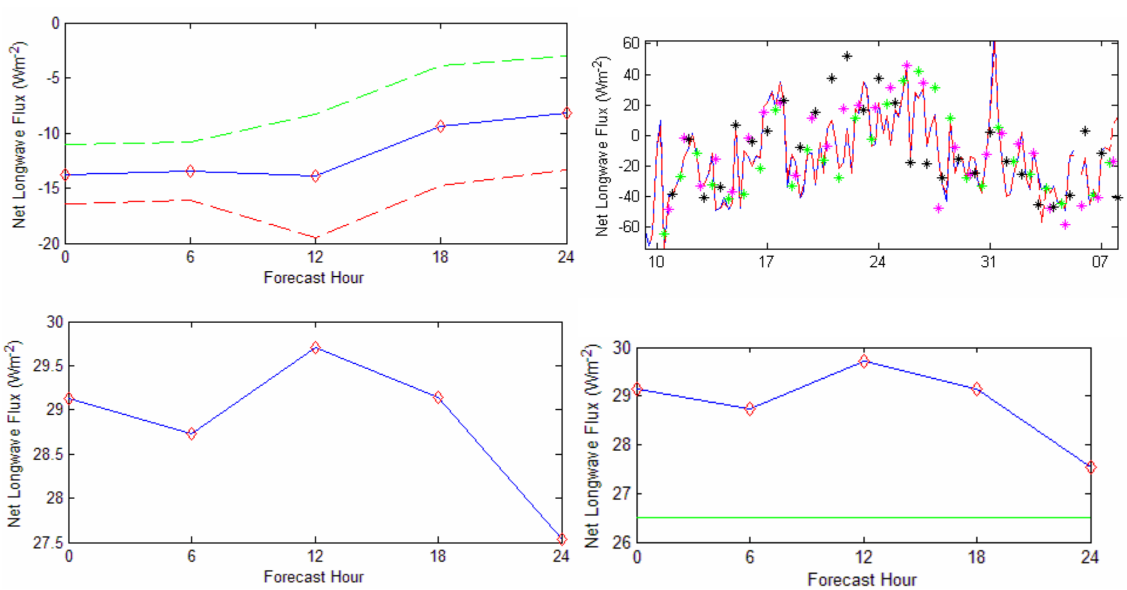

Figure 22. Spring net surface longwave flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

4. Solar Flux

Unlike the winter data set the solar inputs play an important role in the overall surface energy balance. The spring season has the largest solar variability of the entire year. The solar input fluctuates diurnally but, in addition, there is an influence to the net shortwave flux from the amount of clouds present, the surface albedo, and the surface type.

The model tends to have too large of a solar input, which leads to excessive surface heating (Figure 23). A particularly interesting point is that the model appears to have solar input spanning the entire period, with no periods of complete darkness. This can be seen by looking at the minimum peaks. Looking at the differencing (Figure 24) the forecast has a definite diurnal trend, but the difference never goes to zero. The model's RMSd however is well below the standard deviation, so it should be considered to be doing well with its predictions (Figure 24).

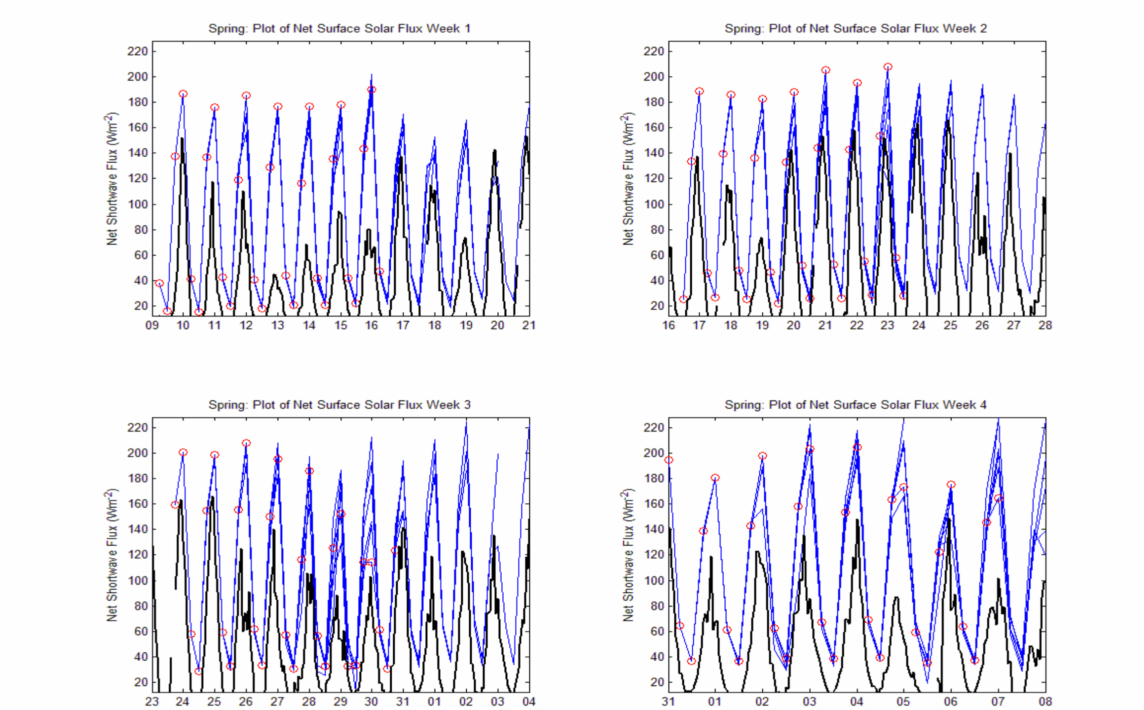

Figure 23. Net surface solar flux for spring period. Representation is similar to figure (4).

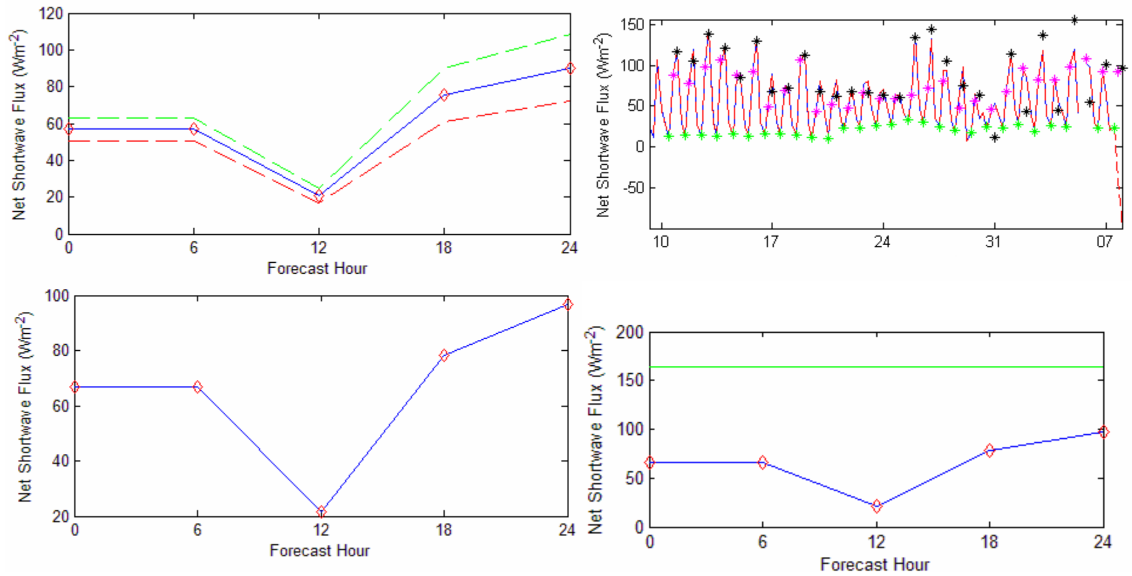

Figure 24. Spring net surface solar flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

5. Ten Meter Wind Speed

There is fairly good correlation of the ten meter wind speed for the two data sets (Figure 25), with only a few of the extended forecasts being erratic. The bias (Figure 26) has only a slightly negative value for the initialization, but remains near zero for the remainder of the 24-hour forecast period. The RMSd is below the standard deviation, so the model appears to be handling the ten meter wind speeds well for the spring period. There is a peak in the RMSd plot (Figure 26) at the 12-hour forecast. The winds seem to have a diurnally forced component that is not entirely picked up by the model.

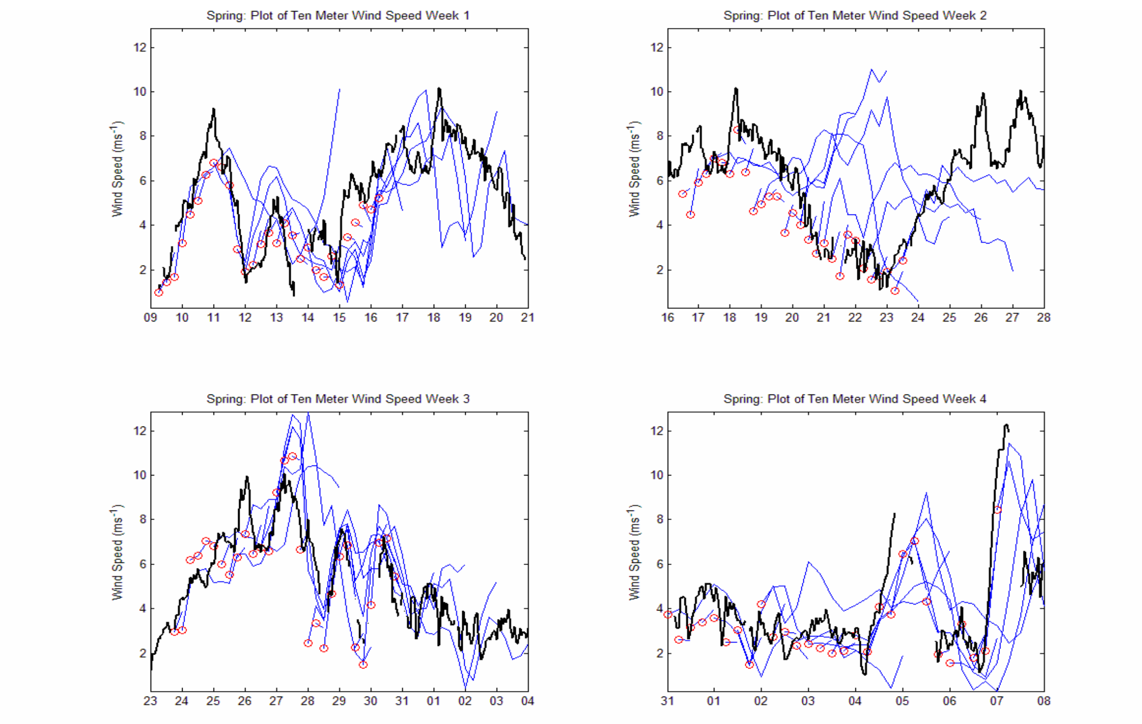

Figure 25. Ten meter wind speed for spring period. Representation is similar to figure (4).

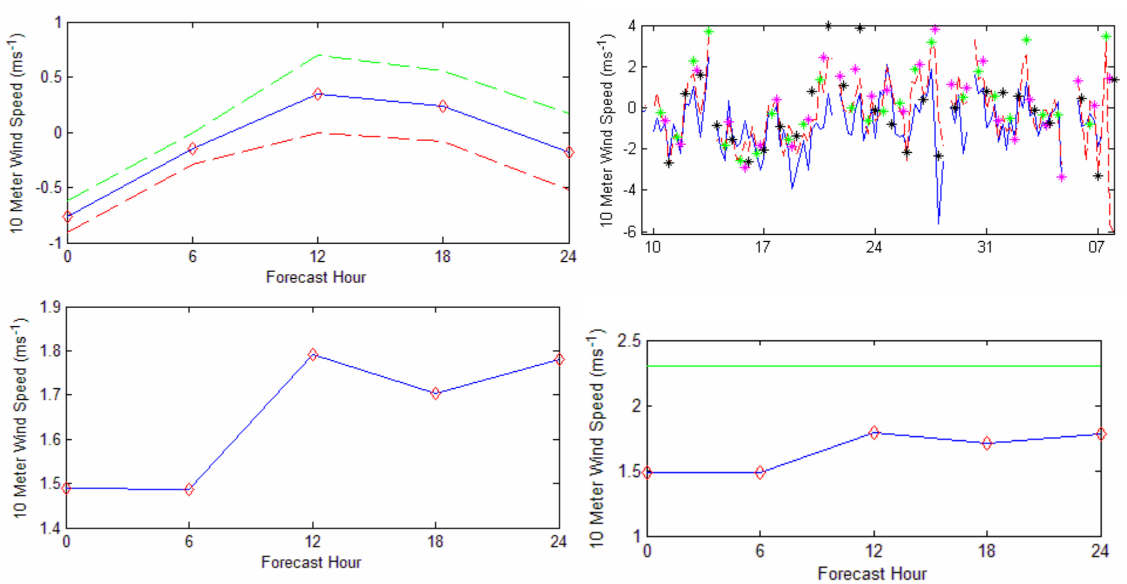

Figure 26. Spring ten meter wind speed plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

6. Two Meter Temperature

NOGAPS has a propensity to drive the temperature to the 273 K point in the first week (Figure 27), reaching 273 K on the 17th while the SHEBA data has a large decrease in temperature starting on the 18th and continues until the 22nd. The model appears to initialize closer to the actual data but immediately progresses to the 273 K mark again. The SHEBA data does not reach the 273 K mark until the 29th. After that point the model and actual data have fairly consistent correlation.

The bias (Figure 28) shows a pronounced bias at the 12-hour forecast, indicating some trouble capturing the diurnal fluctuations. This peak is also present in the RMSd plot. Overall though, the RMSd is below the standard deviation for most of the 24-hour period, but at the 12 and 18-hour forecast periods the RMSd is above (Figure 28). This appears to be due to the diurnal fluctuations being greatest at the 12-hour forecast period.

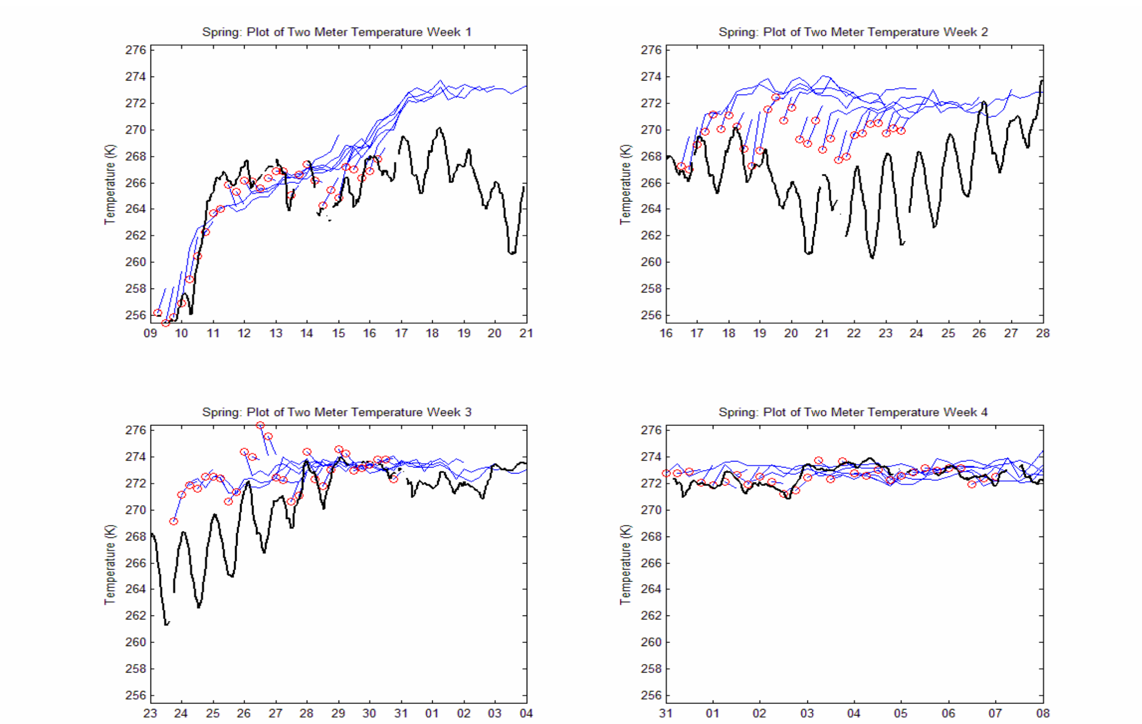

Figure 27. Two meter temperature for spring period. Representation is similar to figure (4).

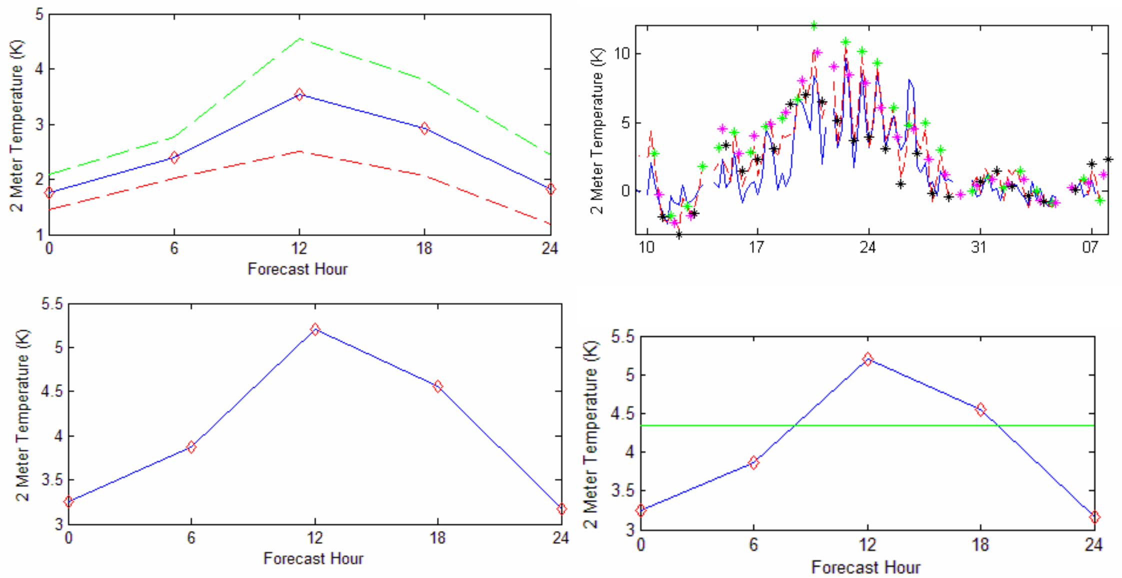

Figure 28. Spring two meter temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

7. Surface Temperature

The rise in temperature seen in the two meter temperature is even more pronounced in the surface temperature (Figure 29). The model does this much more aggressively than is seen in the actual data. The spring data set includes the start of the melt season, when the surface temperature is 273 K. The models predict an earlier onset of the summer melt by 10 days. This is due to a cold event that took place during that period. The same event is present in the two meter temperature plot (Figure 27).

NOGAPS has a small diurnal component in the forecast of surface temperature. The diurnal effect of the SHEBA data is much more prominent, however, and can still be seen in the bias and RMSd plots (Figure 30). The bias is larger for the surface than the two meter temperature. NOGAPS had the surface temperature on the order of 2.5 K warmer than the SHEBA data. From the difference plot, NOGAPS had period with temperatures over 10 K warmer. The RMSd was above the standard deviation by about 4 K for the entire 24-hour period. It was on the order of the bias values which are the contributing factors in the large RMSd difference.

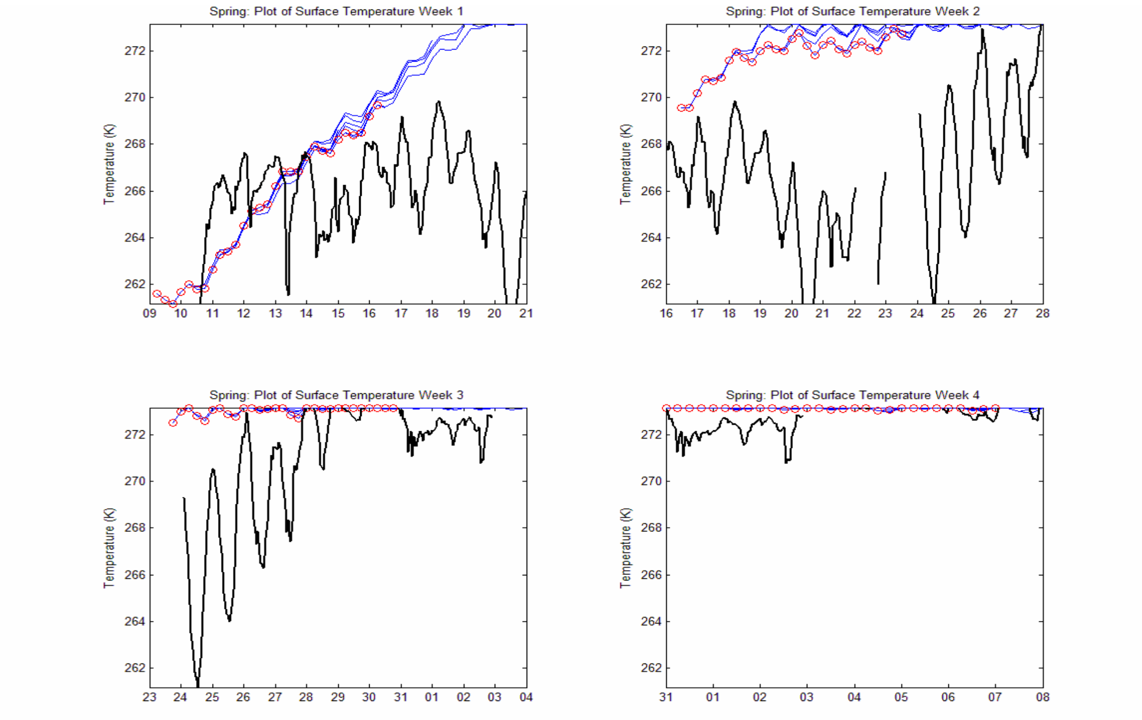

Figure 29. Surface temperature for spring period. Representation is similar to figure (4).

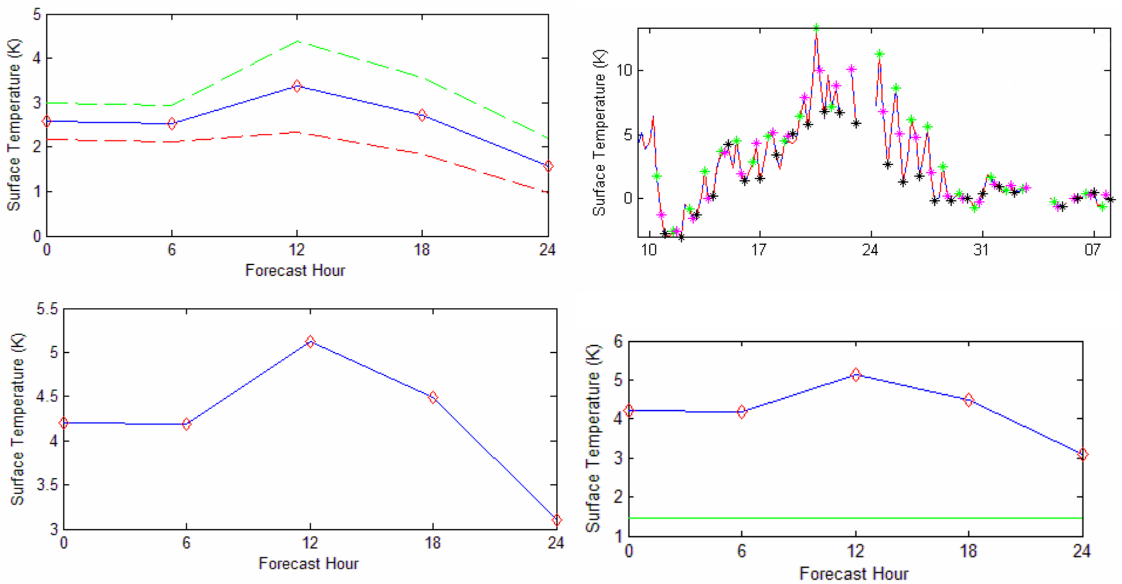

Figure 30. Spring surface temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

8. Low Cloud Fraction

The spring plots of the low cloud percentage (Figure 31) show similar initializations as seen in the winter plots. One difference is the trend of the model to increase the percentages from fifty percent upwards to nearly one hundred percent. This is a change from the winter plots, showing an increase in overall low level cloudiness as the spring season starts.

As mentioned in the winter period, there is a tendency for the Arctic to have a bi-modal cloud distribution of either zero cloud cover or complete cloud cover. Rarely are there partly cloudy conditions observed in the Arctic.

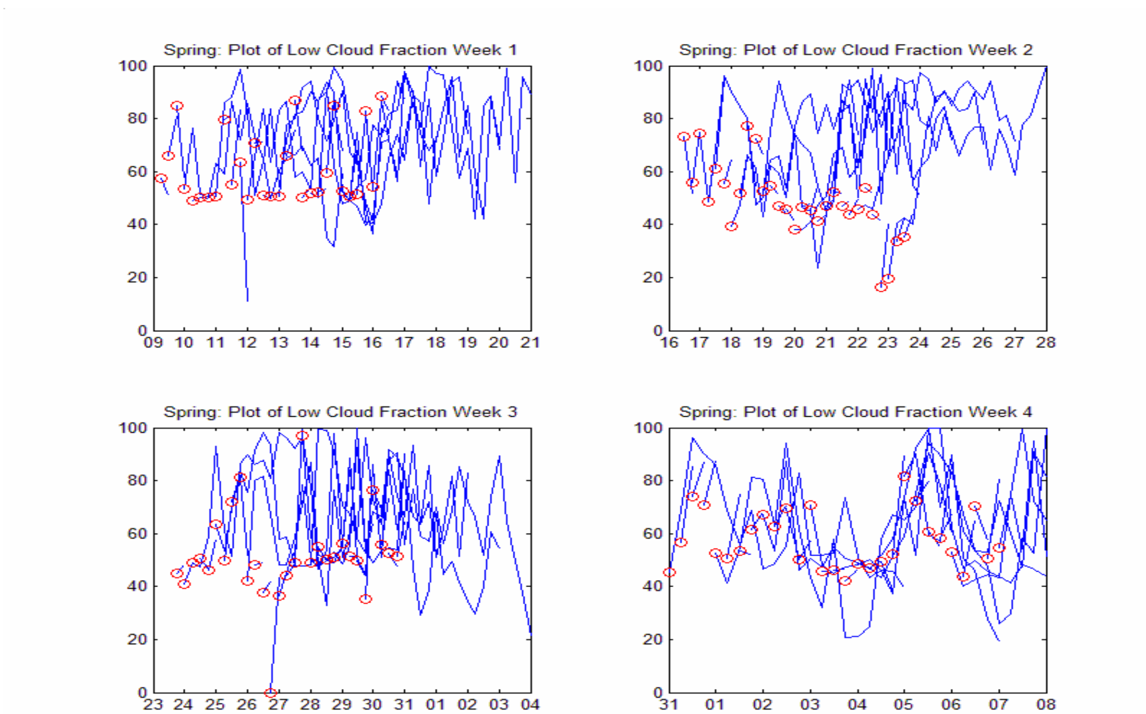

Figure 31. Low cloud percentage for spring period. Representation is similar to figure (4) except no SHEBA data is plotted.

C. SUMMER DATA SET

The summer data set was collected from July 1998 to August 1998. In summer the surface temperature, in general, stays relatively close to the 273 K freezing mark. This is because the melting of the ice causes the surface to maintain a relatively constant temperature as the ice is converted to water. This produces a large amount of relative humidity, which together with cooling of air parcels from the south causes the summer to be mostly cloud covered.

1. Sea Level Pressure

Similar to the previous two seasons the summer has the distinctive correlation of the model initializations to the SHEBA data (Figure 32). The concern for the pressure is the time lags of the extended forecasts in the first week. The model appears to have been able to predict the small changes in the pressure between the 27^{th} and the 31^{st}, but there is a tendency to forecast the events up to a day early. In the second week the model had a tendency to under-forecast the high pressure maximum on the 5^{th}. The extended forecasts were able to accurately forecast the subsequent low on the 9^{th} but, due to the initial forecast being under-forecast, so too was this small dip in the pressure. The profiles of the bias, RMSd, and differencing (Figure 33) have similar results to the previous two seasons.

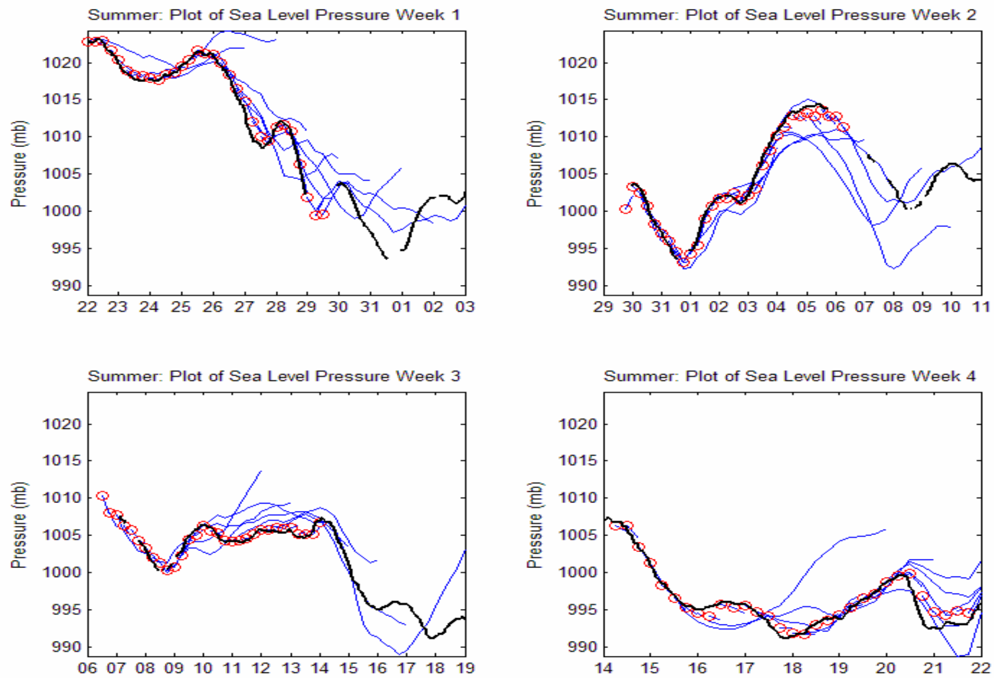

Figure 32. Sea level pressure for summer period. Representation is similar to figure (4).

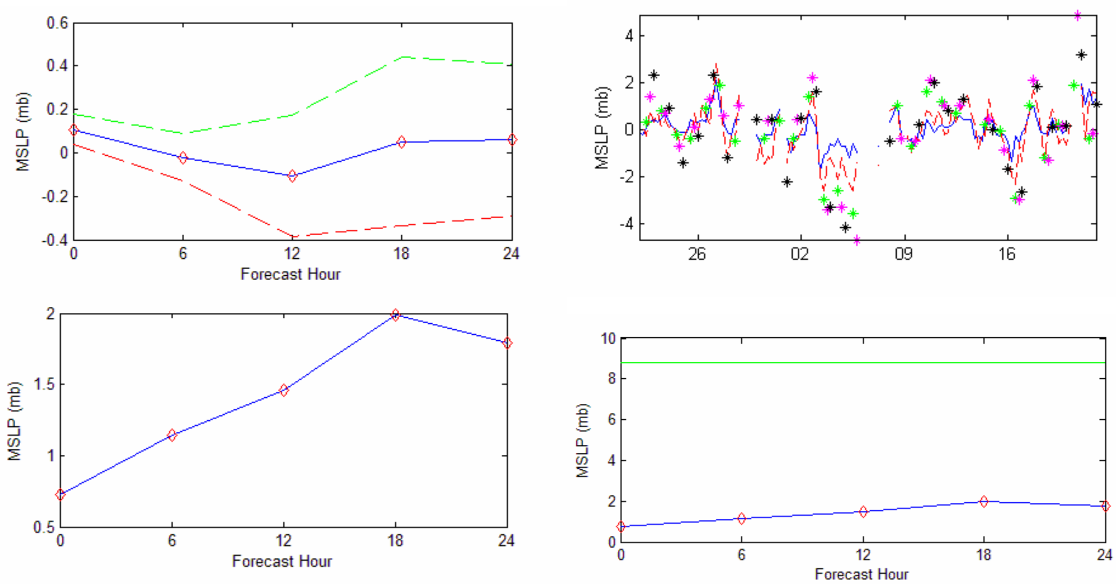

Figure 33. Summer sea level pressure plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to figure (5).

2. Sensible Heat Flux

During the summer the SHEBA data had large sections of data missing from the surface for the sensible heat flux. Data from other tower levels were available but not used in place of the surface data. The small sections of data that were available show a good correlation with the analyses and the forecasts are within 10 Wm^{-2} for those sections (Figure 34).

From the bias plot (Figure 35) there is a small warming bias in the model. The RMSd shows an increasing trend over the 24-hour forecast period, and continually worsens over the entire period

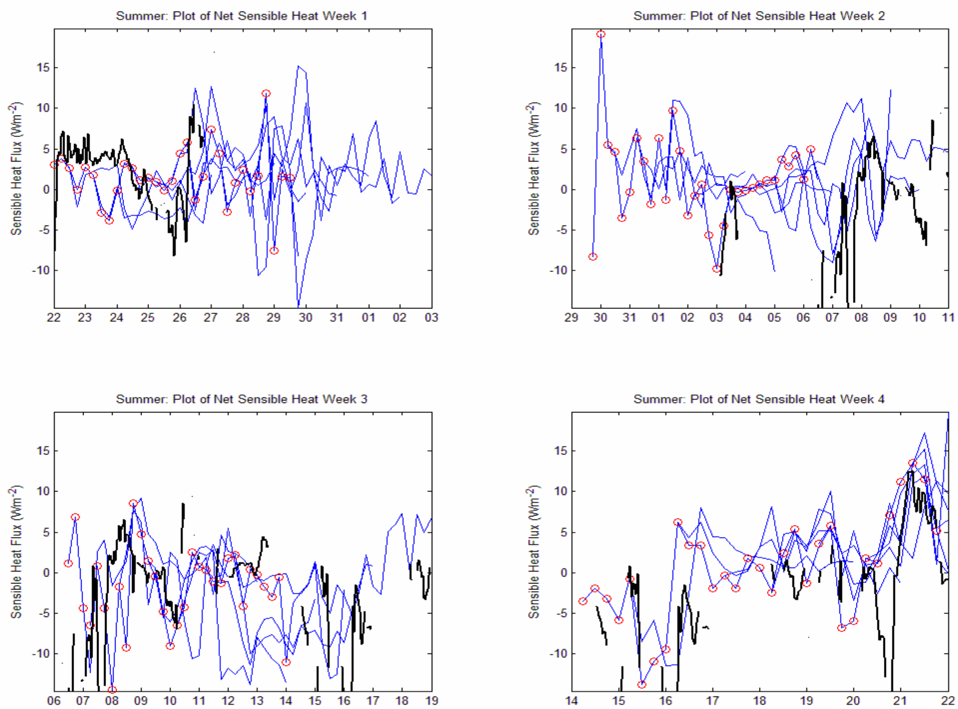

Figure 34. Net surface sensible heat flux for summer period. Representation is similar to Figure (4).

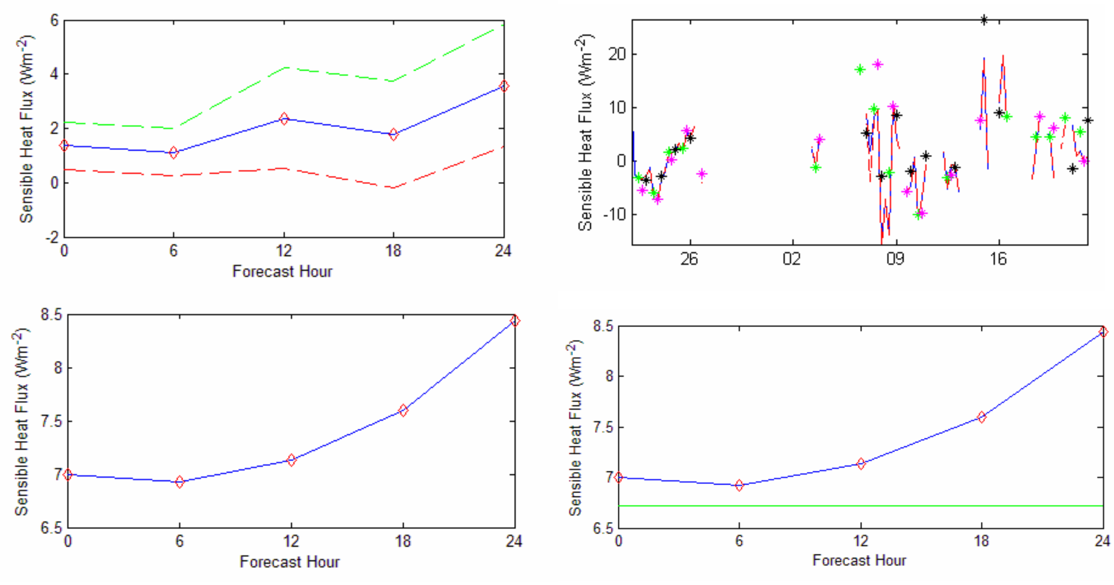

Figure 35. Summer net surface sensible heat flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

3. Longwave Flux

The longwave flux is similar to the previous two seasons. There is large variability in the SHEBA data and also in the model output (Figure 36). As mentioned in the spring section the net longwave flux is a good indicator of whether clouds are present. During the summer, the sky at the SHEBA site was overcast most of the time. Therefore there are fewer of the negative longwave flux peaks associated with clearing. The model however has a larger tendency towards forecasting clearing vise clouds. This is different from the previous two periods since the surface temperature was at 273 K, which suggests that the net longwave flux is due to a lack of longwave flux down to the surface. In the previous two seasons the large temperature difference is the leading cause of the large net longwave flux. The bias plot (Figure 37) shows similar levels of net longwave flux as the previous seasons, but is not as strong. The plot shows a negative flux of approximately -15Wm^{-2} for the 24-hour forecast period, and the RMSd is well over the standard deviation.

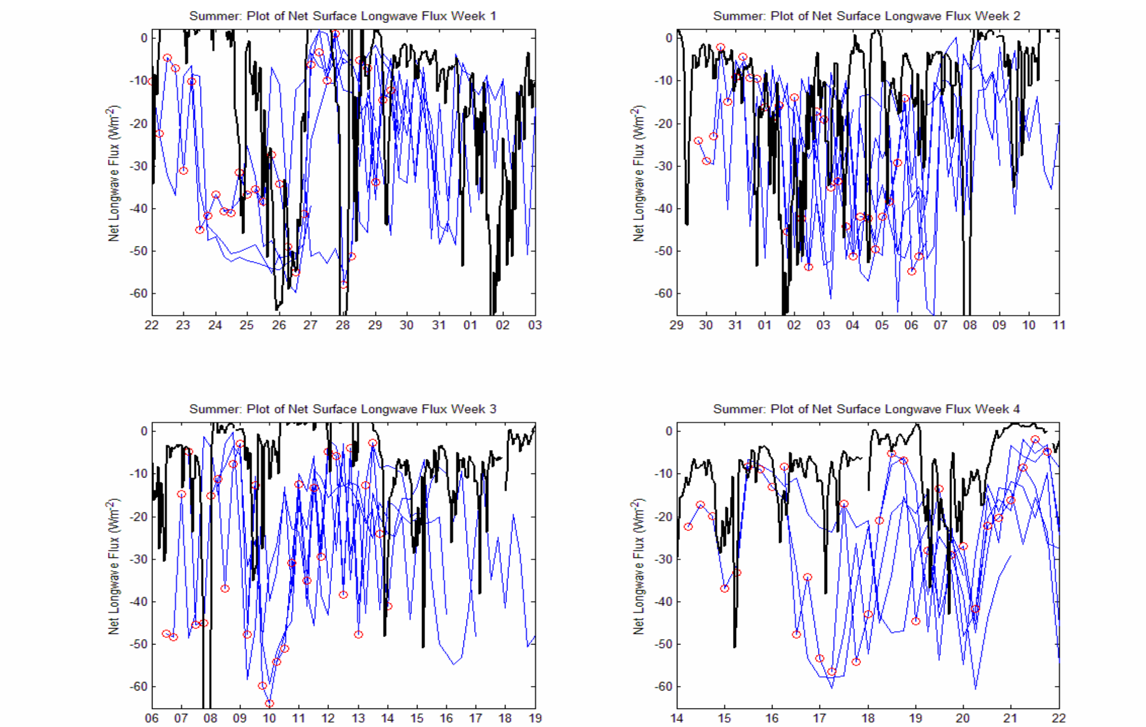

Figure 36. Net surface longwave flux for summer period. Representation is similar to Figure (4).

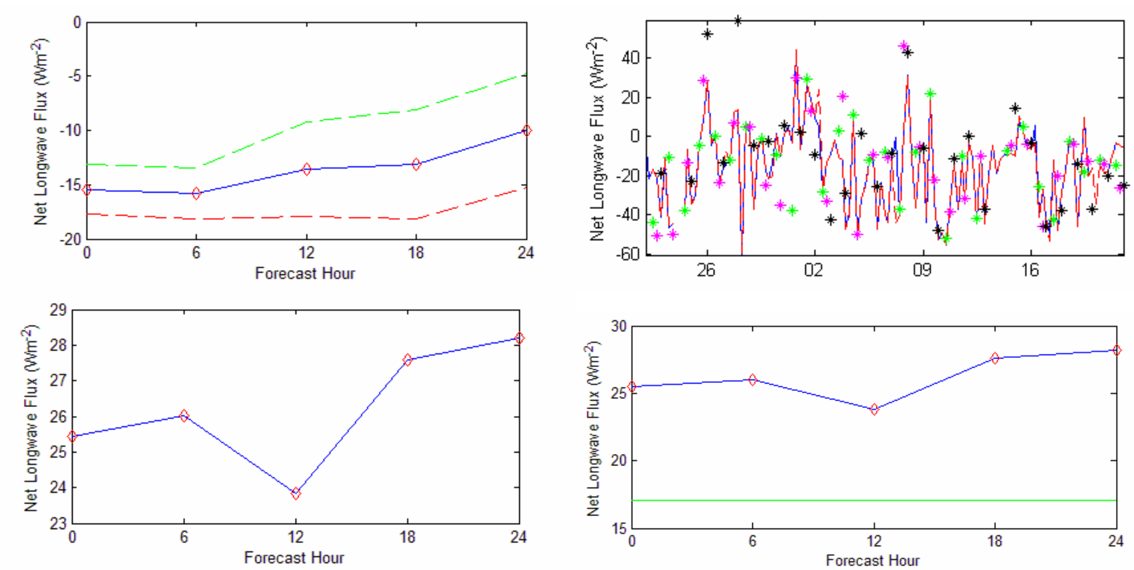

Figure 37. Summer net surface longwave heat flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

4. Solar Flux

The solar fluxes for summer are on par but slightly lower than the spring period. The summer period is the reverse of the spring period, the solar input begins to decrease mid-way through the period as the sun begins to get lower in the sky (Figure 38). It is at its maximum early in the first week, but can be seen to decrease as the weeks progress. The model still has an overall larger input than the actual measured value. As in the spring period the model has a tendency to always have a positive solar input, even during the late evenings when the SHEBA data shows the solar input goes to zero (Figure 38).

The bias (Figure 39) shows a large bias in the solar flux, but there is a diurnal effect that reduces the bias of the 12-hour forecasts to only half the value of the other forecast hours. This dip is also present in the RMSd plot at the 12-hour forecast. The RMSd is well below the standard deviation throughout the entire 24-hour forecast period.

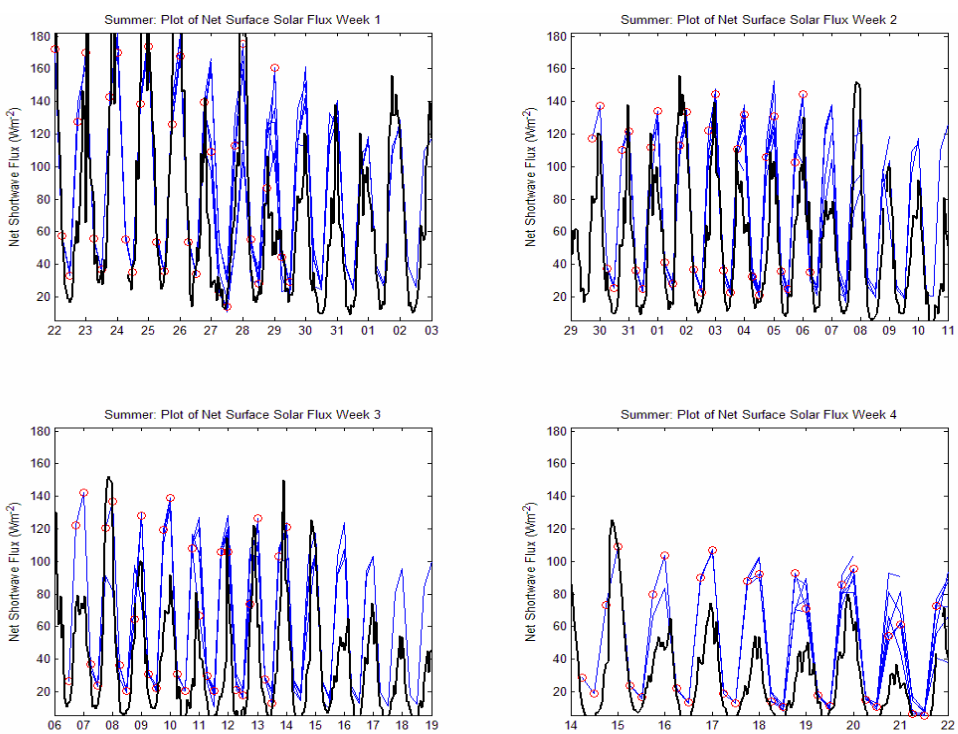

Figure 38. Net surface solar flux for summer period. Representation is similar to Figure (4).

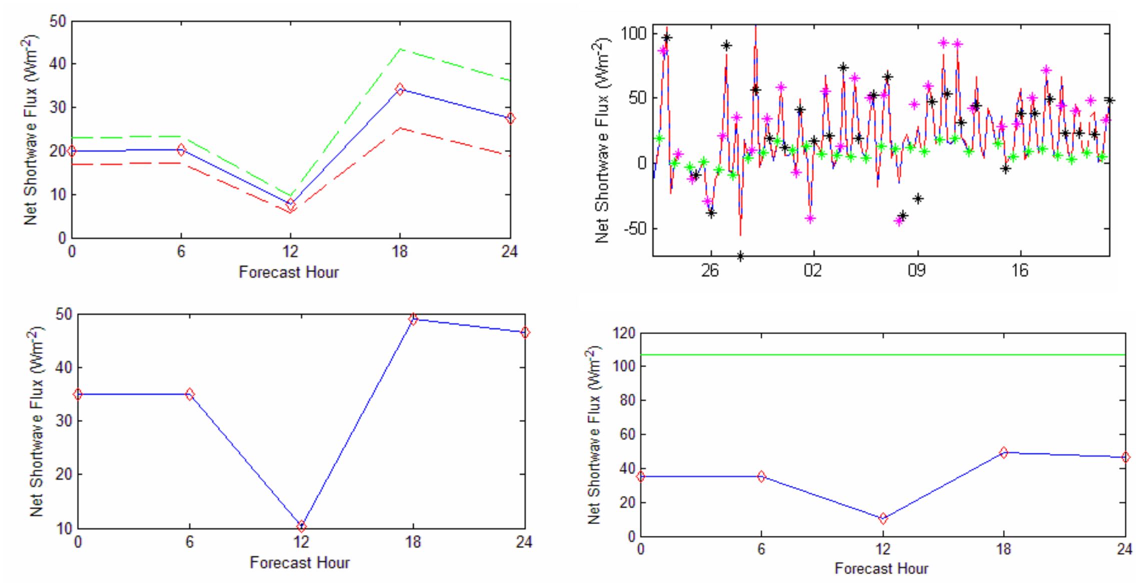

Figure 39. Summer net surface solar flux plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

5. Ten Meter Wind Speed

From the plot of the two data sets there appears to be fairly good correlation (Figure 40). However there is one period where an instrument malfunction occurred between the 28th and 31st. This data was removed from the calculations. The winds during the period had very little variation and the standard deviation values were low for the SHEBA data. The bias for the 24-hour forecast period was nearly zero for the entire period. RMSd for the ten meter wind speed was below the standard deviation for the entire 24-hour forecast period, but it increased from the analysis to the 24-hour forecast (Figure 41).

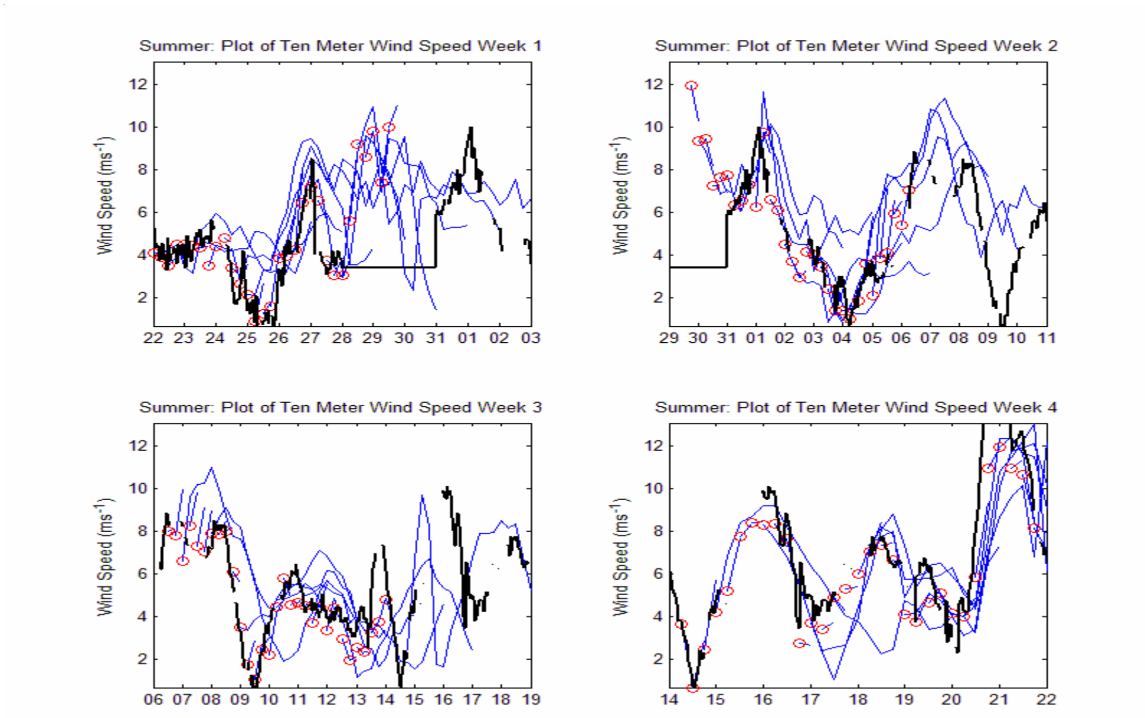

Figure 40. Ten meter wind speed for summer period. Representation is similar to Figure (4).

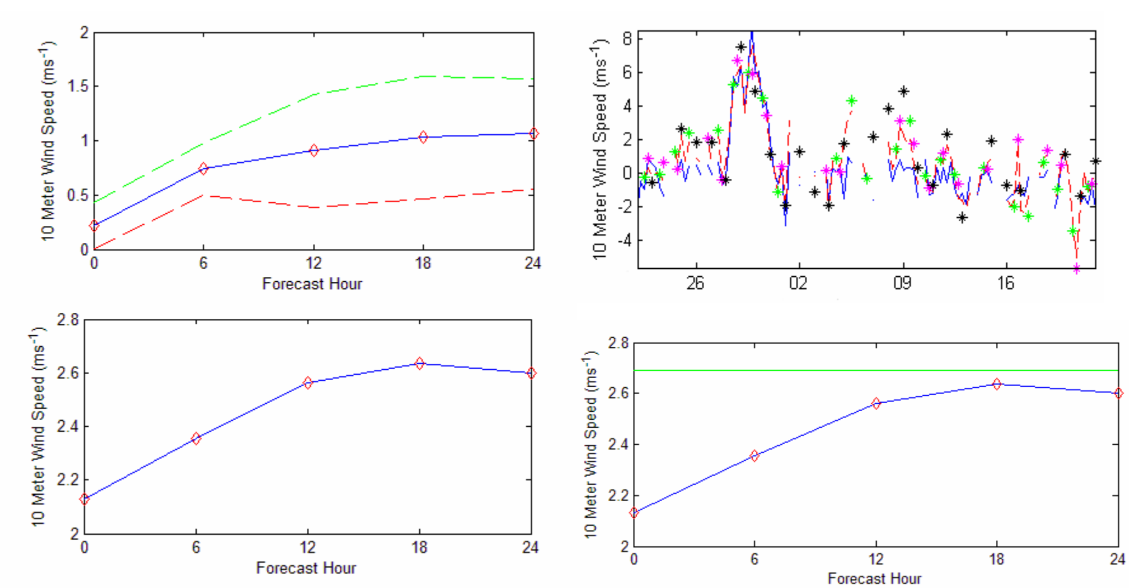

Figure 41. Summer ten meter wind speed plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

6. Two Meter Temperature

The forecast of the two meter temperature during the summer has much smaller levels of variability than seen in the previous two seasons. The analyses and forecasts have similar values and trends but there are a few events that should be noted. The first is the cooling that takes place in the second week on the 31st (Figure 42). The second is another cooling event in the third week on the 13th. From the 13th to the end of the fourth week the SHEBA data was cooler than the model. The model was not able to pick up on these events, and likely has difficulty with the quick fluctuations in surface temperature changes. In general the temperature fluctuations are rather small and the bias (Figure 41) is only slightly positive. The RMSd values are slightly above the standard deviation of the SHEBA data but, due to the small fluctuations during the summer period, does not seem to be significant to the models performance (Figure 43).

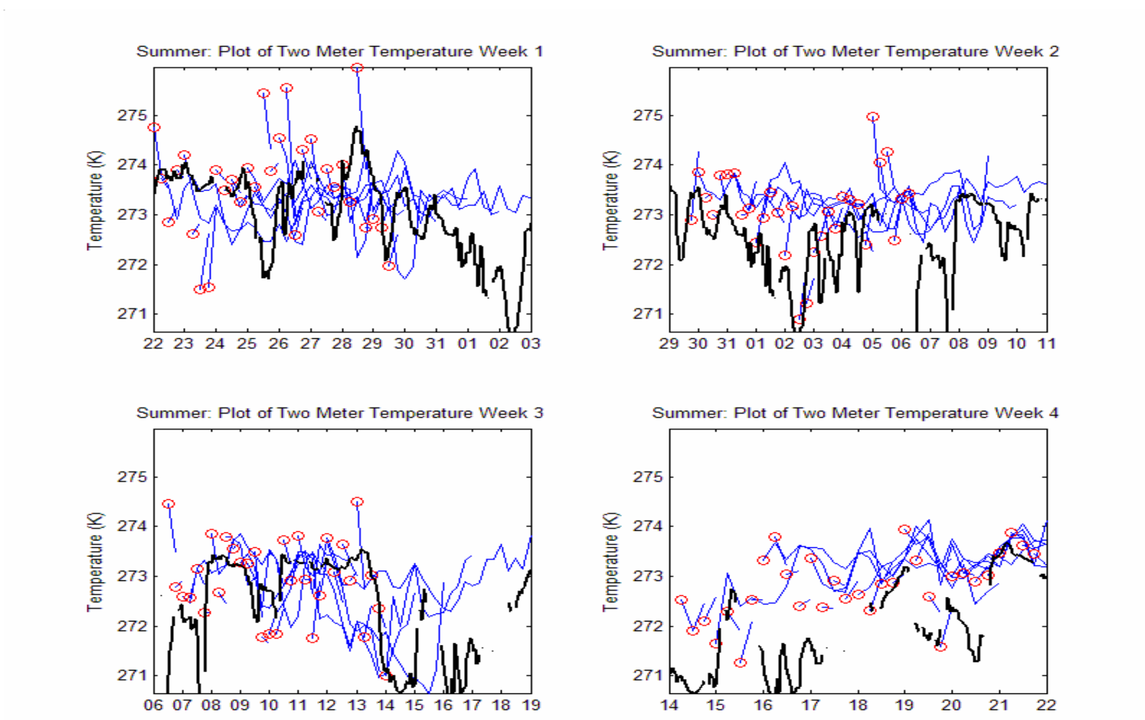

Figure 42. Two meter temperature for summer period. Representation is similar to Figure (4).

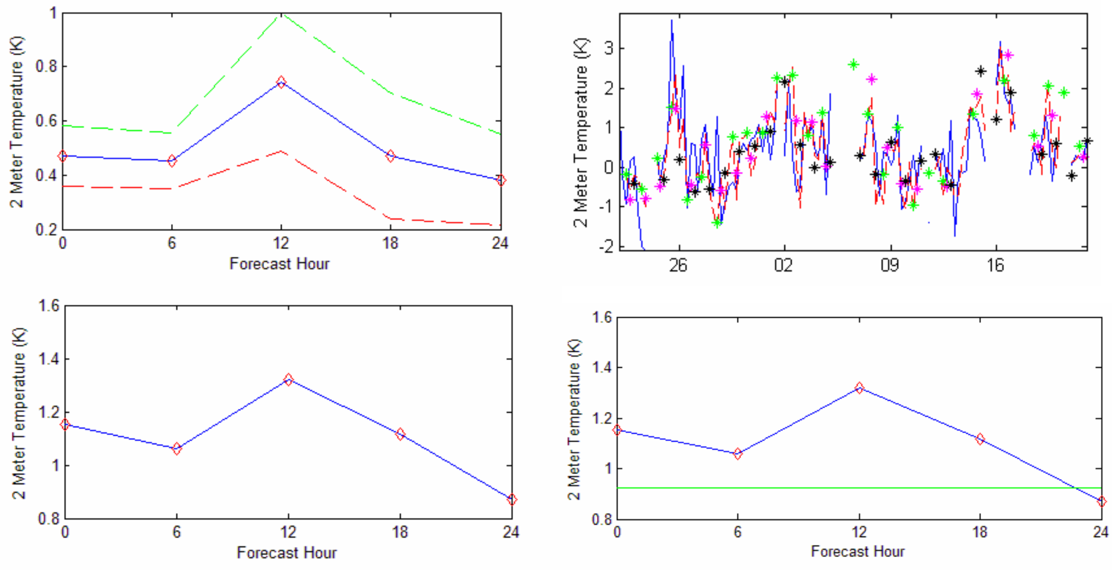

Figure 43. Summer two meter temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

7. Surface Temperature

As mentioned earlier during the summer the surface temperature remains near the 273 K mark as the ice melts. In the plots (Figure 44) the SHEBA data hover around the 273 K mark with only a few periods where there is a cooling event that reduces the temperature by a maximum of only 3 K as seen in the difference plot (Figure 45). The bias has a very small diurnal trend at the 12-hour forecast (Figure 45). The RMSd value hovers about the standard deviation, and is only slightly worse than the standard deviation at the 12-hour forecast (Figure 45). This is similar to the two meter temperature, in that the small levels of fluctuation in the SHEBA data during the summer would suggest that this finding is not critical to the model's performance during the summer period. NOGAPS correctly simulates the relatively constant surface temperature, but this means summer is not an ideal period to determine whether NOGAPS was properly handling the thermodynamics.

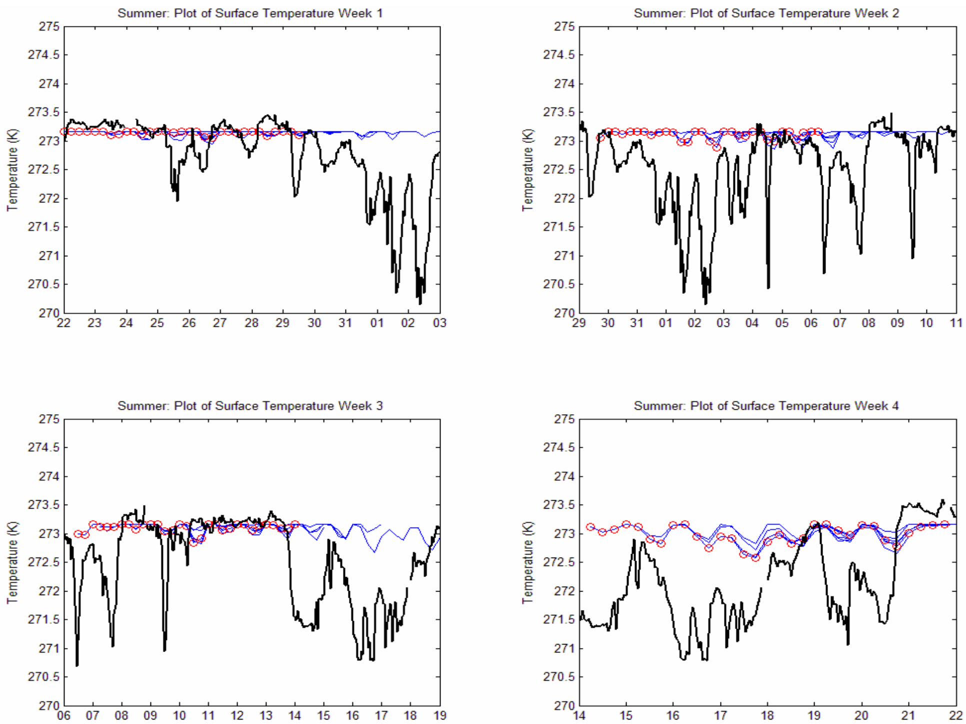

Figure 44. Surface temperature for summer period. Representation is similar to Figure (4).

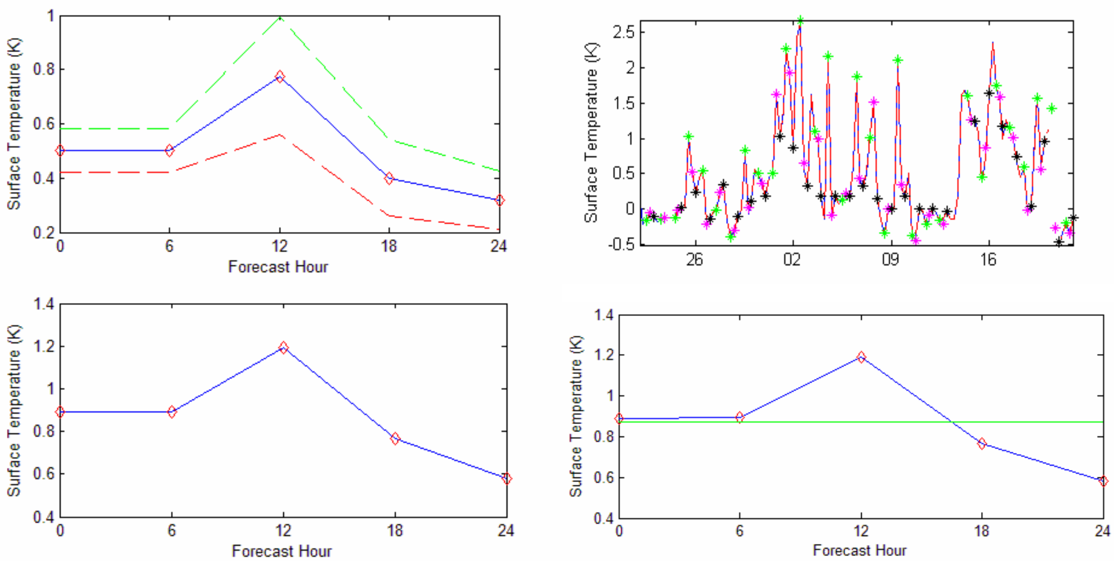

Figure 45. Summer surface temperature plot of bias, differencing, RMSd, and standard deviation comparison. Representation is similar to Figure (5).

8. Low Cloud Fraction

The low cloud percentage has similar results to the spring period, but as stated earlier summer periods tend to have nearly one hundred percent cloud cover for most of the period. The net longwave flux suggested that there were only a few periods where there were any cloud breaks (Figure 36). The summer period has a tendency to initialize at the fifty percent level and increase to as high as one hundred percent (Figure 46).

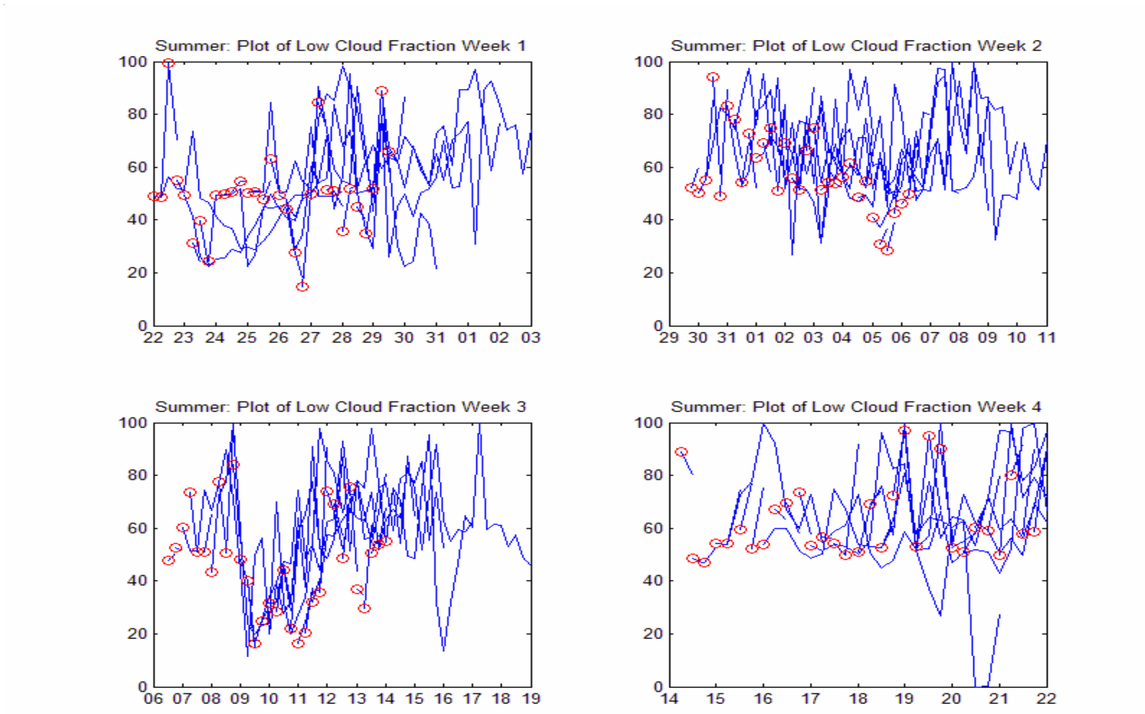

Figure 46. Low cloud percentage for summer period. Representation is similar to Figure (4) except no SHEBA data is plotted.

V. SUMMARY AND CONCLUSIONS

A. NOGAPS PERFORMANCE

The variables used to define how well the Arctic is modeled are the net longwave flux, the solar flux, cloud distribution, surface and two meter temperature, sea level pressure, and the ten meter wind speed. The standard deviation of the SHEBA data provided a standard by which to evaluate the model performance in handling the physics of a variable.

NOGAPS did well with the prediction of the sea level pressure and the ten meter wind speeds. The initializations for these two parameters were very close to the SHEBA data values and since they followed closely to the data with their forecasts it appears the physics behind these parameters is well defined. The extremely low bias for these two parameters is either due to their being available in the archive of data used to initialize NOGAPS or other parameters used to initialize NOGAPS (e.g. the mass field) were relatively accurate

The comparison of the two sets of data over the three periods identified potential problems in the model physical parameterizations. The symptoms of these problems include a surface and near surface air temperature that responds too slowly to changes in forcing and a generally to warm surface temperature. Also the model net longwave flux cools too much and has large RMSd values due to the difficulty in predicting cloud cover.

In the spring and summer periods the solar inputs were too high. The summer period had more bias than the spring, 70 Wm^{-2} vs. 25 Wm^{-2} for the 24-hour forecast. The variations in solar radiation compared well between the model and the measurements and in both the spring and summer the RMSd was well below the standard deviation.

The biases and RMSd differences in predicted vs. observed surface temperature cannot be explained by the biases in net fluxes used in this study. Instead the reverse seems to be the case; biases in the surface temperature appear to be driving the flux biases. For example the net longwave radiation and sensible heat flux cool the surface in the model greater than the observations and this does not cause the surface to be too cold,

in fact the surface is too warm and the fluxes are responding to that by transporting more heat from the surface. Looking at the plots of surface temperature in the spring (and to a lesser degree the summer) periods, the diurnal forcing (24-hour temperature variations) is much smaller in NOGAPS compared to SHEBA. For the winter and spring periods, the NOGAPS surface temperature seems to be driven toward a slowly varying underlying value. For example, if the model initialized too far from this value, the following forecasts from the model would adjust toward the value. In the winter the temperature remained close to 245 K for the entire period. In the spring there was an increase of temperature from 262 K to 273 K over the period of ten days. Lastly the summer had the temperature remaining constant near the 273 K level. In all three cases the actual temperature showed significantly greater shifts from colder to slightly warmer. To test whether the equilibrium temperature seen in the NOGAPS data is a result of the net longwave flux or simply being controlled by the sun angle, future studies could set the model to run with the longwave flux contribution, due to the clouds and atmospheric gases, removed (commented out in code). By removing these components of the longwave flux, if NOGAPS continues to produce similar results, any insensitivity to downward longwave fluxes could be established.

As mentioned the net sensible heat and net longwave flux extracted more heat from the surface than observed and yet the surface temperature remained warmer during most of the periods studied. It would seem that with larger temperatures than the SHEBA data, there must be something causing the extra warming. With the both the net sensible heat and net longwave fluxes both showing cooling taking place there must be another source for the heating seen. The direct latent heat fluxes observed from SHEBA had instrument problems but bulk estimates indicate the magnitudes of latent flux were usually less than 5 Wm^{-2} and could not have caused the observed warm surfaces. NOGAPS also showed cooling from the latent heat so this cannot be the culprit for excessive heating in the model. The only issue that was not looked at in this study is the conduction of heat to the surface from the ice and underlying ocean. The solar flux heating was not large enough to offset the longwave cooling and in the winter when the solar flux was zero, the same problem was present.

NOGAPS uses a one-layer representation of sea ice and does not explicitly model the snow surface that is usually present. This gives the surface too much "thermal inertia" because the whole ice floe must change temperature instead of just the top few centimeters. In reality, dry snow has very low heat conductance and capacity and therefore the snow surface responds rapidly to changes in thermal forcing. To capture these variations more accurately, a numerical model needs several layers within the ice and snow on the floes, particularly near the top. The warm surface temperatures during the winter also suggest that the NOGAPS ice may be conducting too much heat from the ocean upward. This may be a compensation for the lack of explicit lead and open water parameterization. Whereas SHEBA was just based on ice flow measurements, NOGAPS grid cells include open water areas, and therefore the high surface temperature may be a way to implicitly include open water and thin ice effects.

The last area of concern in this study was the way in which NOGAPS produced clouds. In all three periods looking at the lower level clouds formed, NOGAPS consistently produced clouds in the fifty to ninety percent range. In only a few cases, did the NOGAPS cloud cover exceed the ninety percent or get below the fifty percent. One of the predominate features of the Arctic is the presence of a bimodal cloud distribution pattern. Most of the time the observed low level clouds in the Arctic were either one hundred percent coverage, or zero coverage, unlike the NOGAPS predictions. An overall trend in all variables was for NOGAPS to miss the maxima and minima in diurnal cycles. The large diurnal trend is a key factor in the way NOGAPS differs from the SHEBA data. In the biases of all variables there appears to be a significant difference at the 12-hour forecast periods. This suggests that NOGAPS is not properly handling the extent of ranges seen in the data or is taking too long to respond to changes in the variable.

B. POSSIBLE IMPROVEMENTS

One of the key issues with the model is the way in which it deals with the surface and the heat capacity of ice, if present. The extremely small fluctuations in the surface temperature are suggestive of issues with the NOGAPS's thermal inertia for heating the surface. If the model is attempting to adjust the temperature of the entire ice surface, this would explain the small fluctuations. To alleviate these issues a better representation of

the surface would be appropriate. Using multiple layers such that quick changes in the surface energy fluxes can affect the upper surface temperature would be more representative of what is actually taking place in the Arctic. Ultimately, being able to determine whether the surface is comprised of ice, snow, open ocean, or a combination of these types between the grid points would be a better way of representing the Arctic feedback loops.

Right now the model only determines whether the surface at the grid point is either ice or open ocean. This does not account for whether there are leads and polynas, which can account for significant levels of heat transfer from the ocean to the atmosphere. The model would benefit from using satellite data to determine location, size, and frequency of leads and polynas in the Arctic. By incorporating this data into the model as an overlay on its grid system, a better estimate for the energy flux at the surface could produce more accurate forecasts of clouds, frontal systems, and cold air mass formations.

The solar inputs seen in the spring and summer had a tendency to be slightly too large and, at times, never went to zero, when in reality the SHEBA data reflected that it went to zero. Modifications to the optical depth and/or the albedo to bring these values closer would help to prevent excess solar heating in NOGAPS.

Clouds in all three periods began their initializations at (or near) the fifty percent point. NOGAPS initializes from a “cold” start, with no clouds initially and must “spin-up” any clouds from initial conditions. Making an improvement to the Arctic cloud structures in the model to reflect the Arctic’s trend of the low cloud coverage to be either 0 or 100 percent would create a more realistic energy balance for the Arctic.

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